

Orion Thermal Protection System Independent Review Team

NASA's Efforts to Understand and Respond to Artemis I Heat Shield Char Loss

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Orion Heat shield IRT Report

Orion Thermal Protection System Independent Review Team

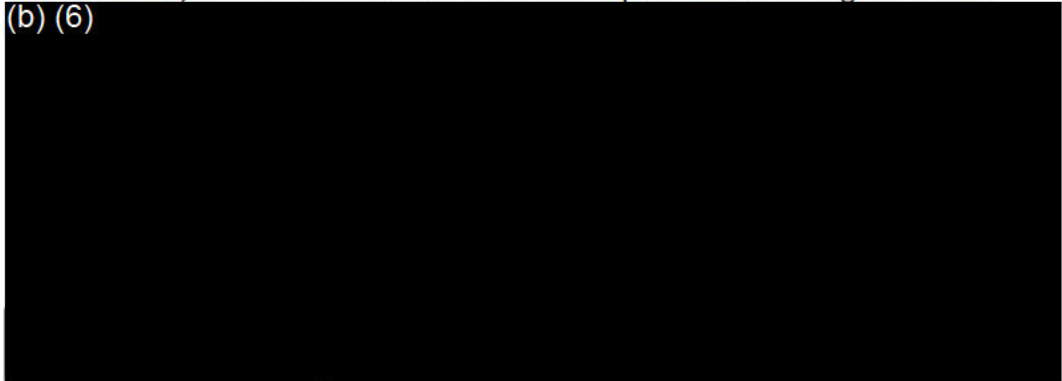
(b) (6)



Paul Sean Hill

NASA retired, former JSC Director of Mission Operations and Flight Director

(b) (6)



Warren "Woody" Hoburg

NASA Astronaut

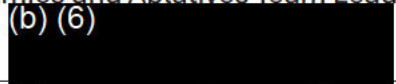
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Sarah Howse

Ceramics and Ablatives Team Lead, NASA MSFC Engineering Directorate

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Michael T. Kirsch

Deputy Director, NASA Engineering & Safety Center

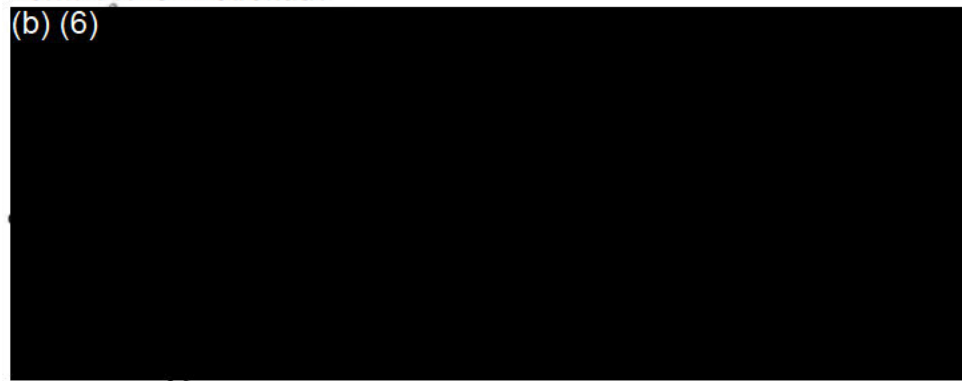
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John "Danny" Olivas

Former NASA Astronaut

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Aerosciences Technical Fellow, NASA Langley Research Center (retired)

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Mairead Stackpoole

Thermal Protection Materials Branch Chief, NASA Ames Research Center

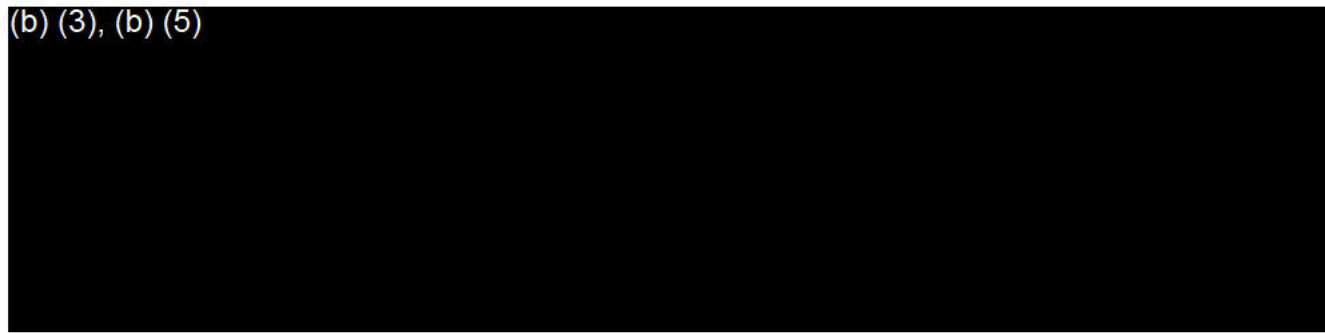
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Executive Summary

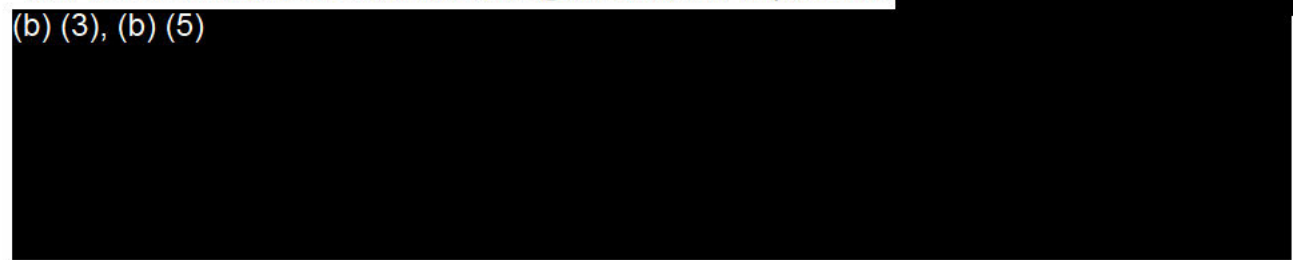
Artemis I, which deorbited December 11, 2022, was the second uncrewed test flight of the Orion spacecraft and the first to fly a lunar return, skip entry, and a block Avcoat heat shield. Unlike Orion's first entry during Exploration Flight Test-1 in 2014, the Artemis I heat shield experienced extensive and anomalous spalling of the ablative material's outermost, charred layer. Although charring is a normal ablator behavior during entry, the heat shield is not designed nor was it expected to liberate sizeable pieces of this char. Instead, an Avcoat outer char layer is intended to recede gradually, while the underlying material insulates the spacecraft from high heat flux during entry.

(b) (3), (b) (5)



The Orion Program stood up a focused Heat Shield Tiger Team (HSTT) to determine root cause, corrective actions, and potential flight rationale for the Artemis II heat shield that had already been fabricated and installed on the Orion vehicle. The tiger team's analytical and test work has been substantial, significant, and impressive. (b) (3), (b) (5)

(b) (3), (b) (5)



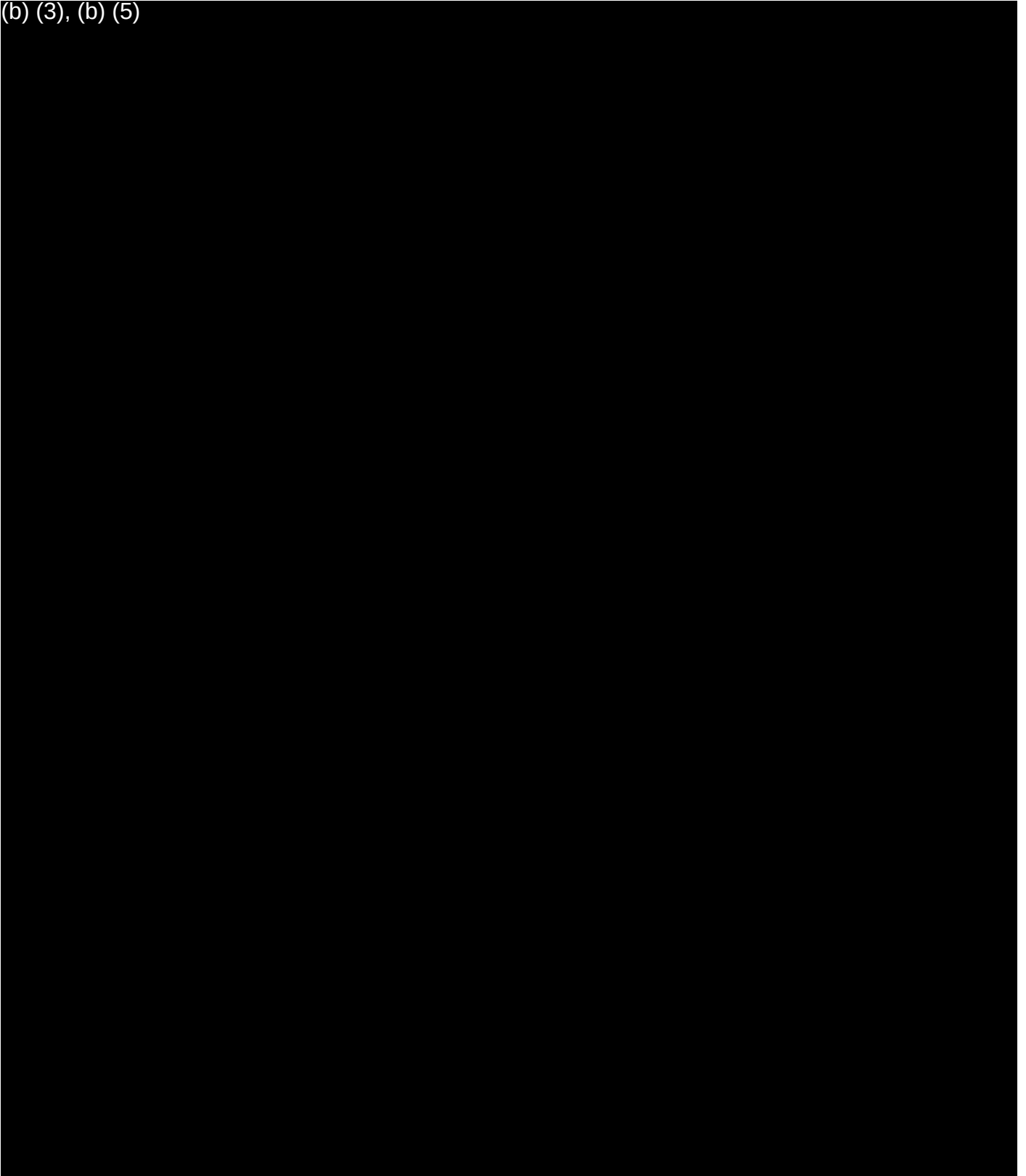
In April 2024, NASA chartered an Independent Review Team (IRT) to evaluate the HSTT's (b) (3), (b) (5)



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Root Cause and Corrective Actions

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(b) (3), (b) (5)



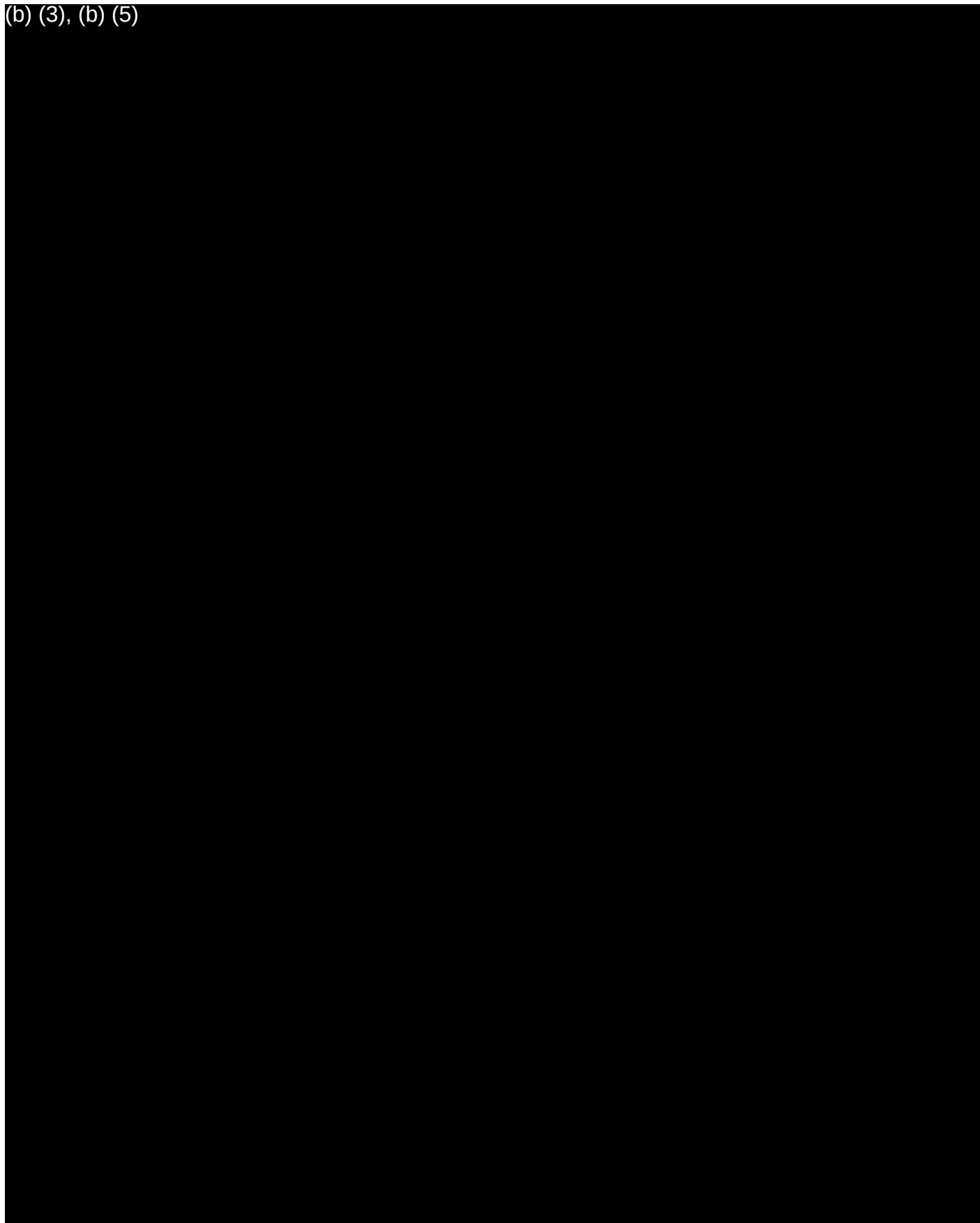
Artemis II Heat shield Flight Rationale

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Orion Heat shield IRT Report

(b) (3), (b) (5)



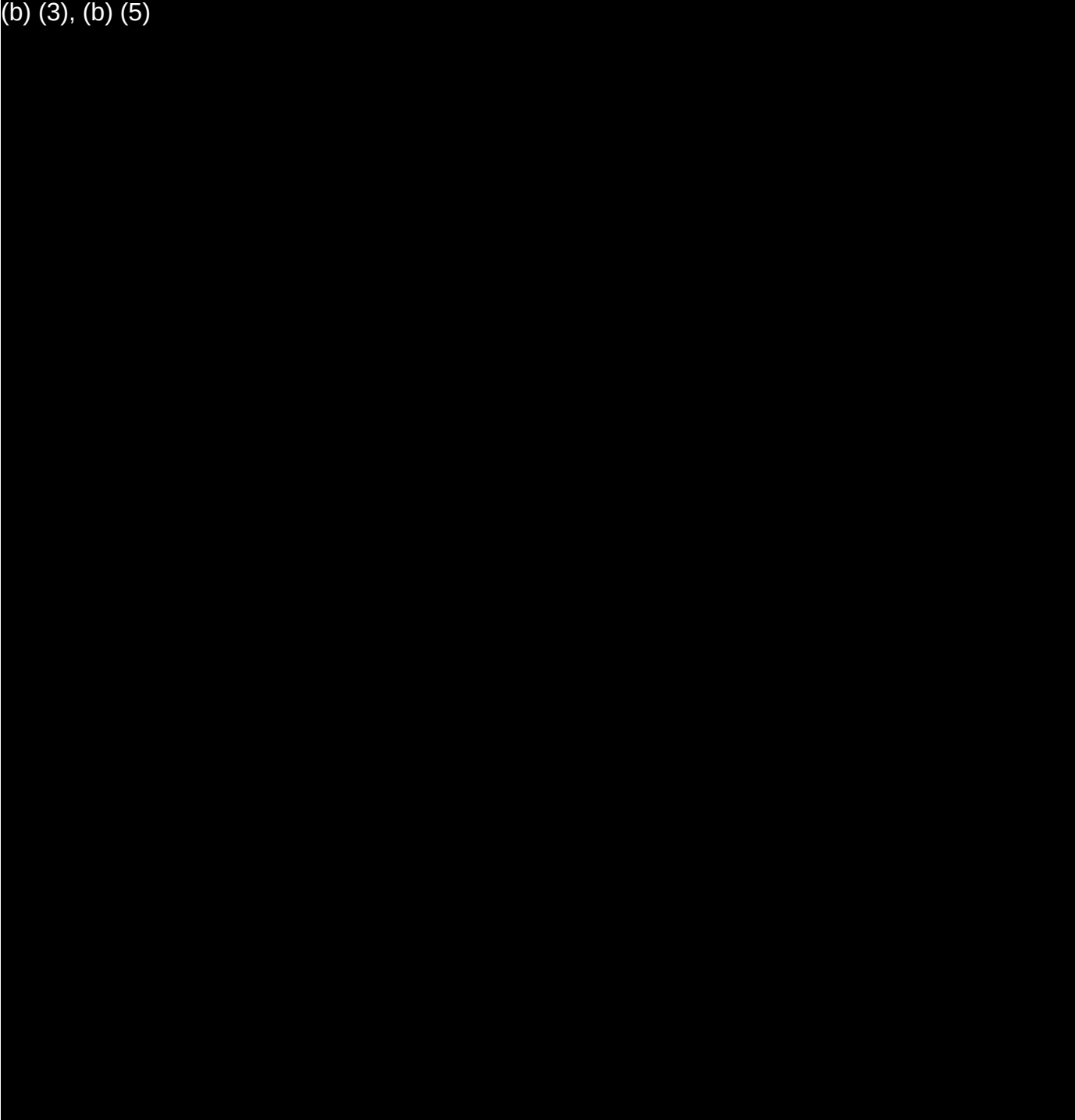
Orion Heat shield IRT Report

(b) (3), (b) (5)



Remaining concerns, uncertainties, and other key observations:

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Orion Heat shield IRT Report

The report elaborates further on these observations as well as the more detailed questions the IRT was formally asked to consider in our evaluation.

Acronyms

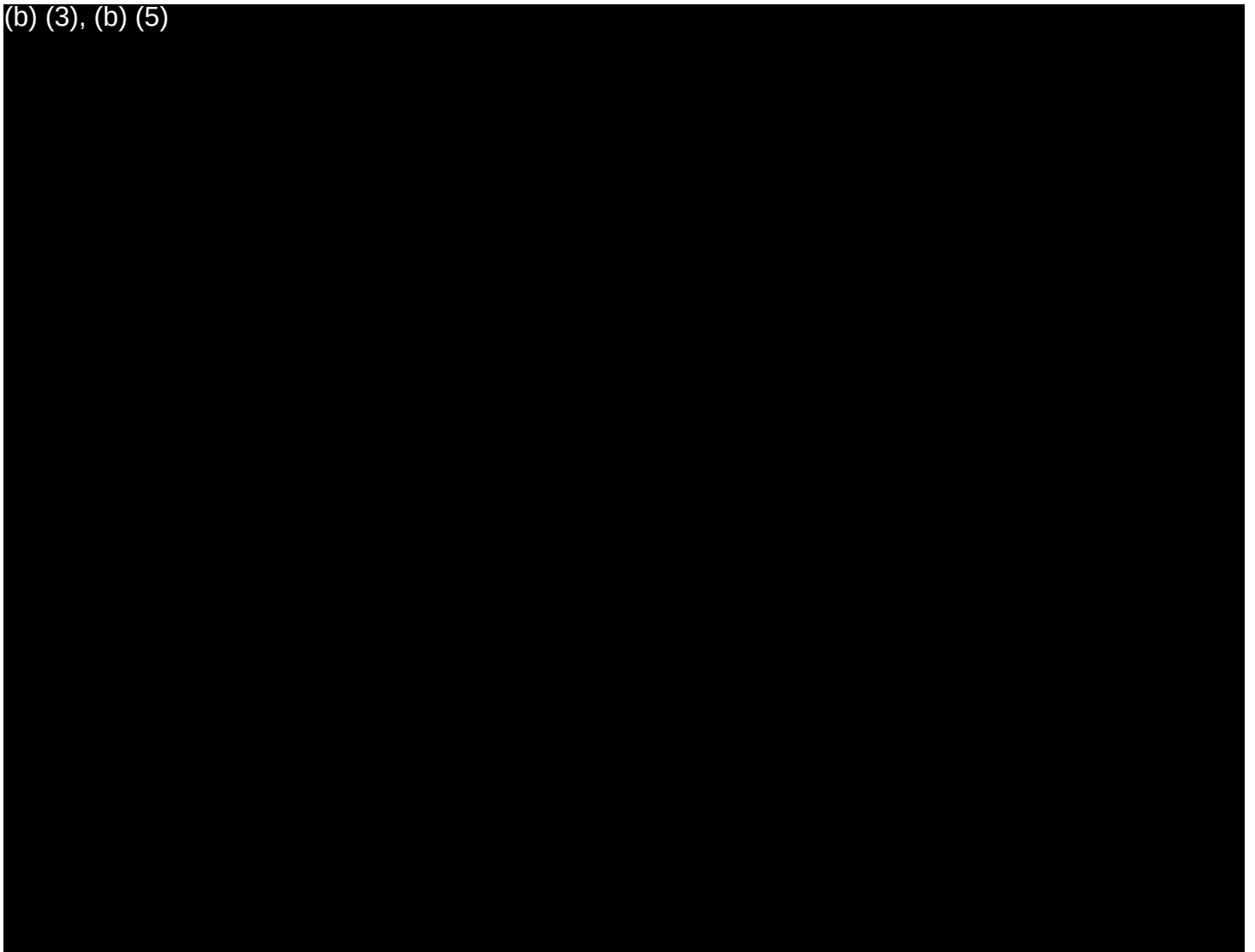
BET	Best estimated trajectory
CBR	Constant bank rate
CT	Computed Tomography
DR	Density ratio (batch density / billet density)
GFE	Government furnished equipment
HDR	High density ratio
HEO	High earth orbit
HS	Heat shield
HSTT	Heat Shield Tiger Team
IP	In-plane
IRT	Independent Review Team
ISS	International Space Station
JSC	Johnson Space Center
LDR	Low density ratio
LEAF	Laser Enhanced Arcjet Facility
LEO	Low earth orbit
MAF	Michoud Assembly Facility
MSFC	Marshall Space Flight Center
NESC	NASA Engineering and Safety Center
NRHO	Near-rectilinear halo orbit
NSTTF	Sandia National Solar Thermal Test Facility
OML	Outer mold line
ρ	Density
RTV	Room temperature vulcanizing
SSP	Space Shuttle Program
WSTF	White Sands Test Facility

1 Introduction

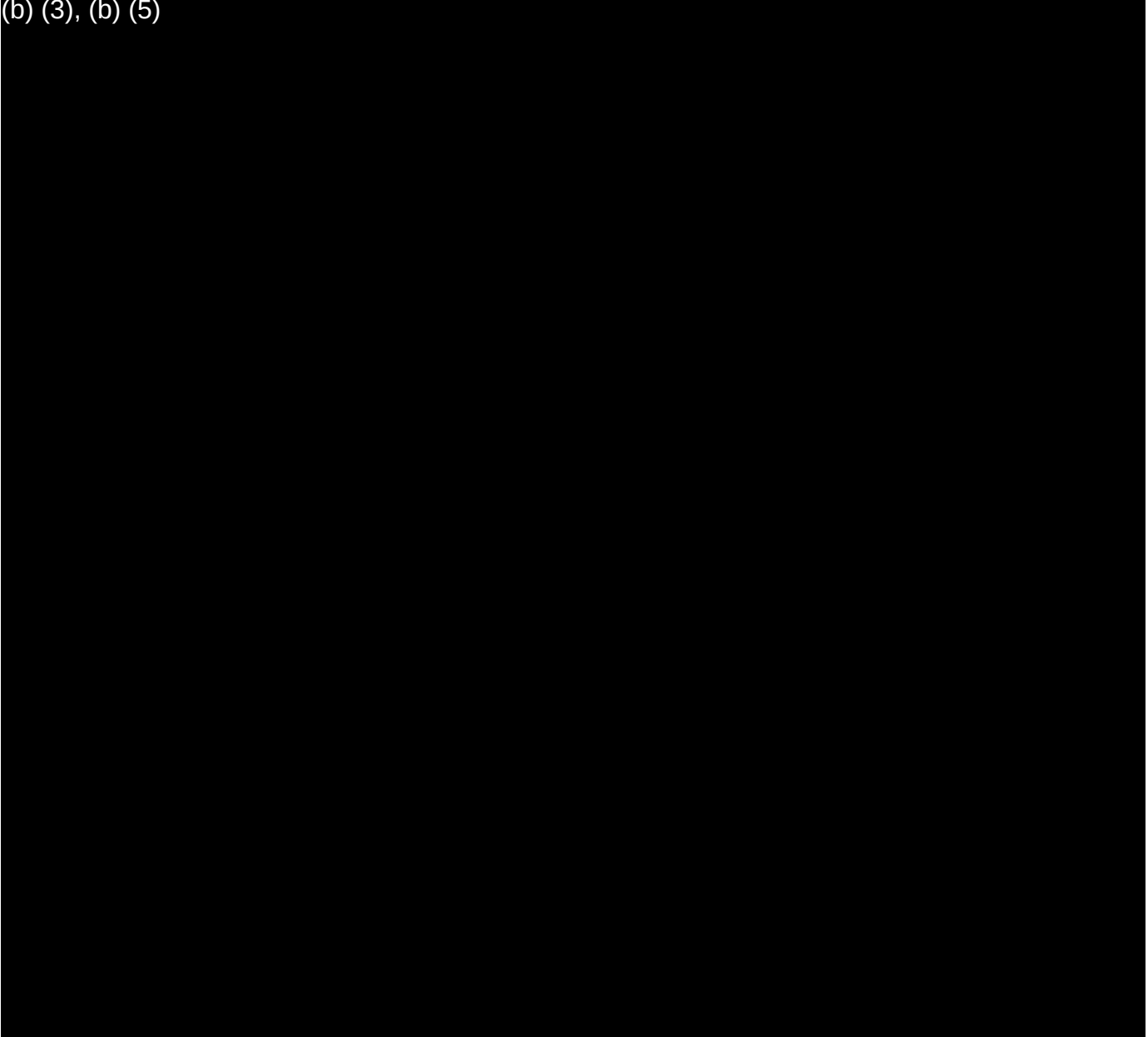
1.1 Background

Artemis I deorbited December 11, 2022, experiencing extensive and anomalous spalling of the ablative material's outermost, charred layer. The Orion Program stood up a focused Heat Shield Tiger Team (HSTT) to determine root cause, corrective actions, and potential flight rationale for the Artemis II heat shield that had already been fabricated and installed on the Orion vehicle. In April 2024, NASA established an Independent Review Team (IRT) "to review and provide assessment of the data that has been generated to date by NASA and its contractors to understand the root cause of the Artemis I Orion heat shield char loss phenomenon and mitigations for future Artemis missions."

(b) (3), (b) (5)



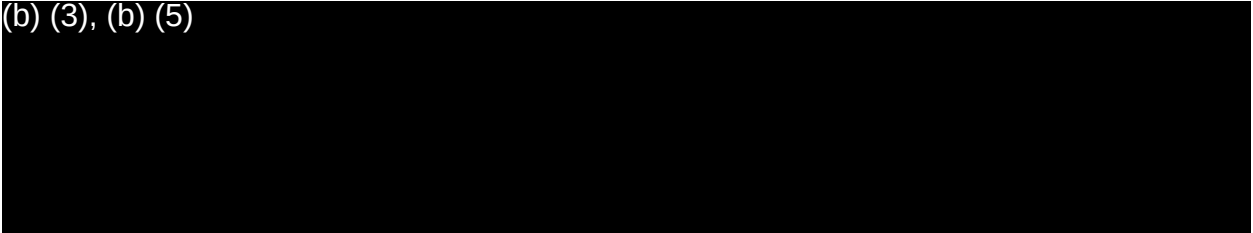
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1.2 IRT Approach

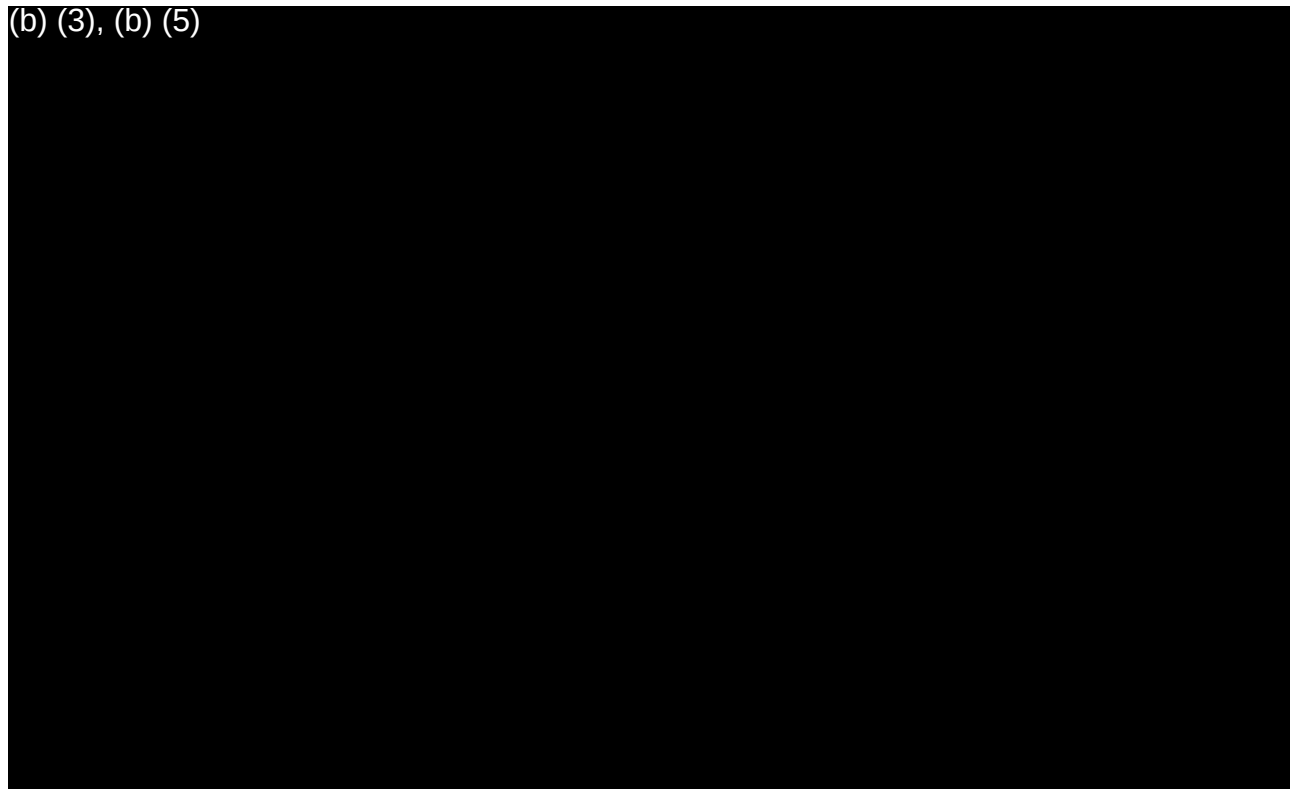
In 2024, NASA directed the IRT to evaluate and make recommendations for the following specific topic areas:

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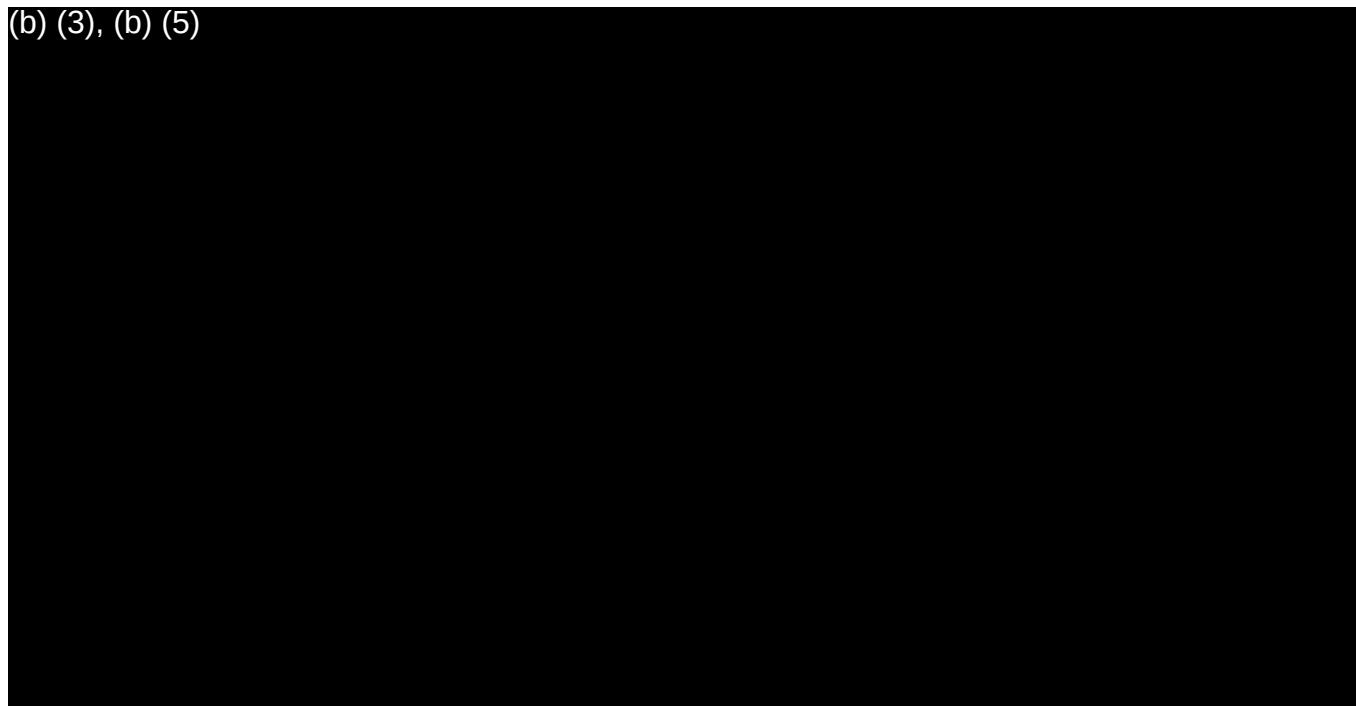
Orion Heat shield IRT Report

(b) (3), (b) (5)



These questions formed the basis of the IRT interaction with the HSTT and this report. Although IRT observations regarding these topic areas are represented throughout the report, they are also each answered succinctly in Section 2.1, Short Answers to the Questions Posed to the IRT.

(b) (3), (b) (5)



Orion Heat shield IRT Report

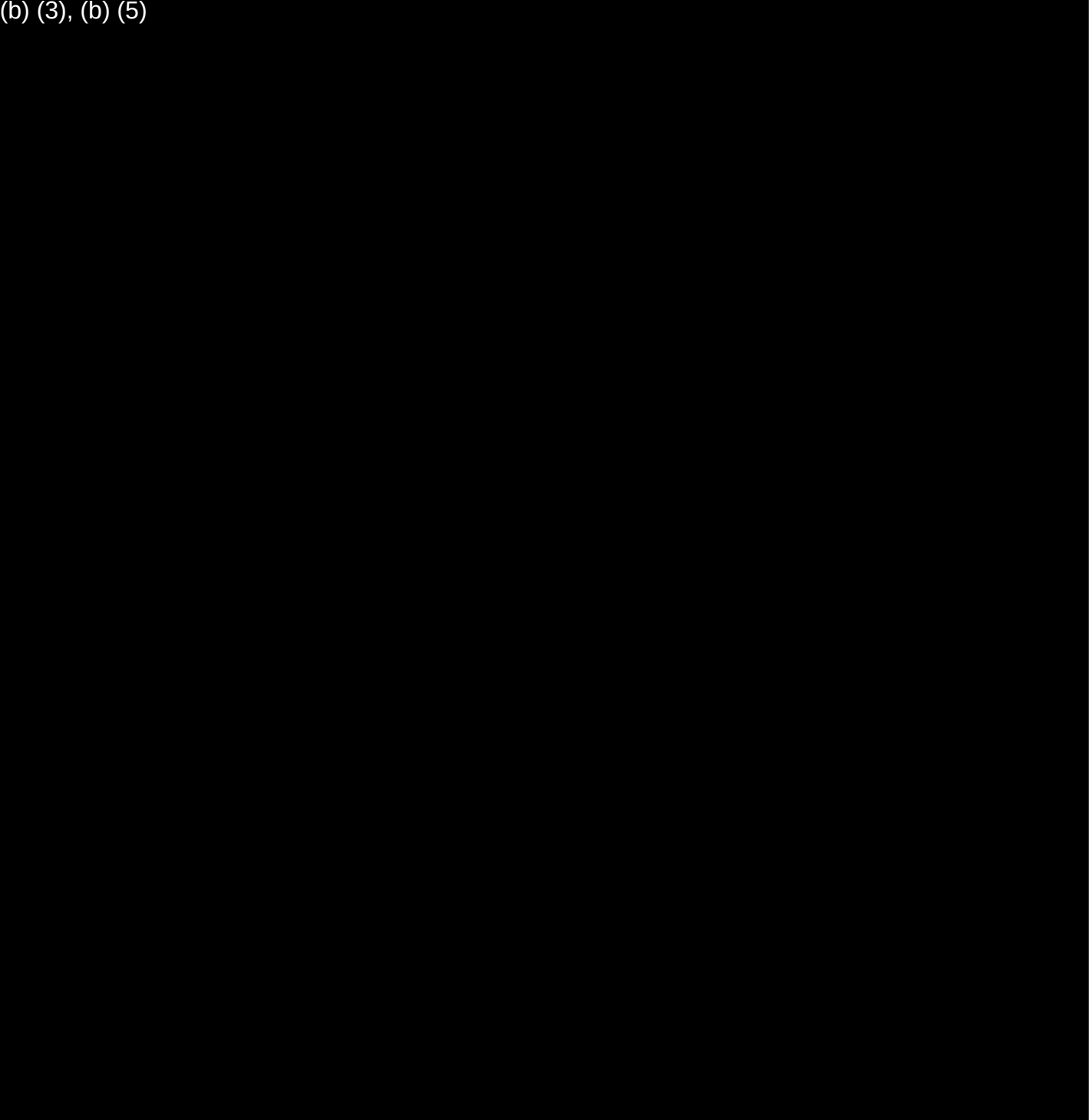
(b) (3), (b) (5)



2 IRT Observations and Recommendations

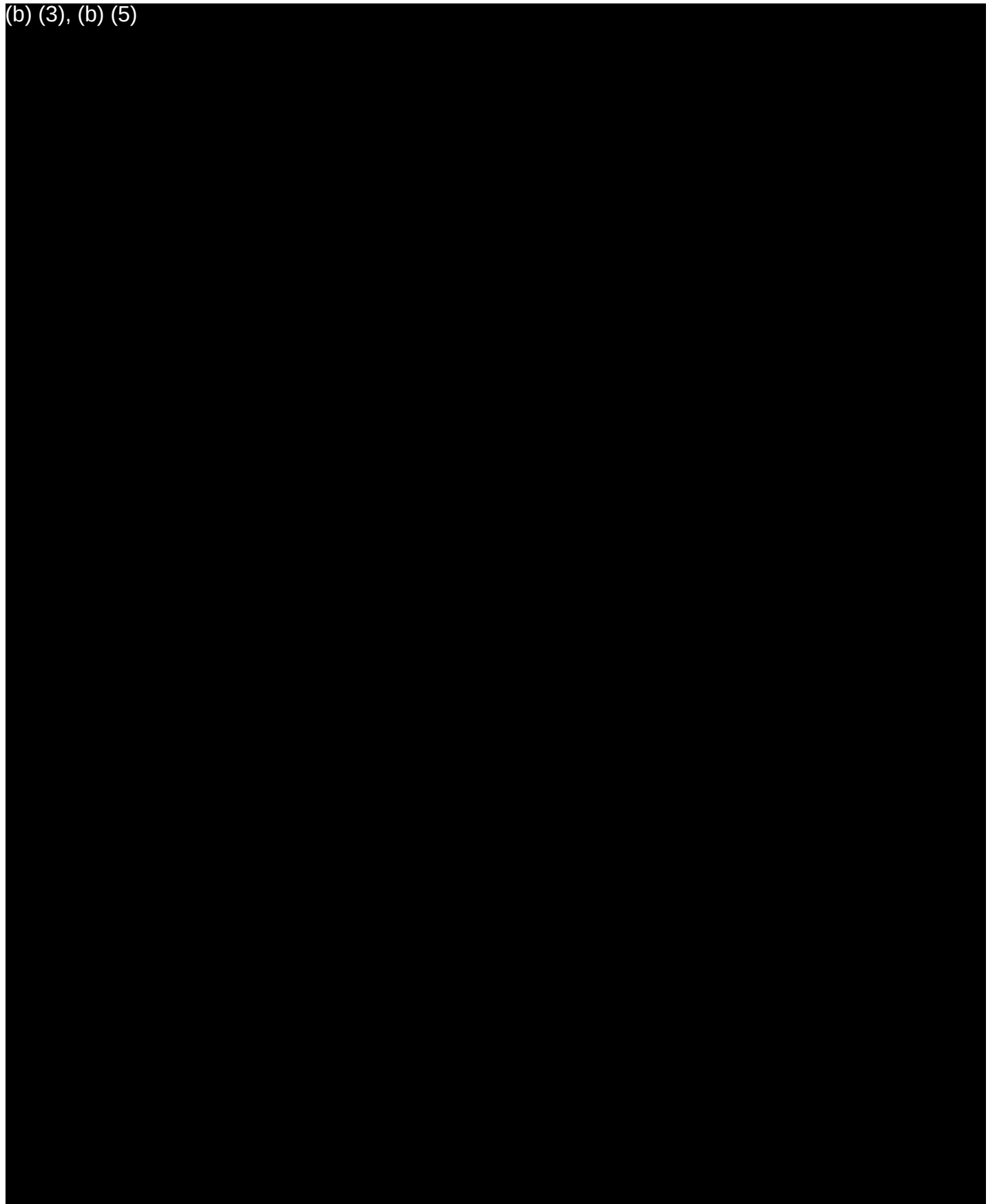
2.1 Short Answers to the Questions Posed to the IRT

(b) (3), (b) (5)



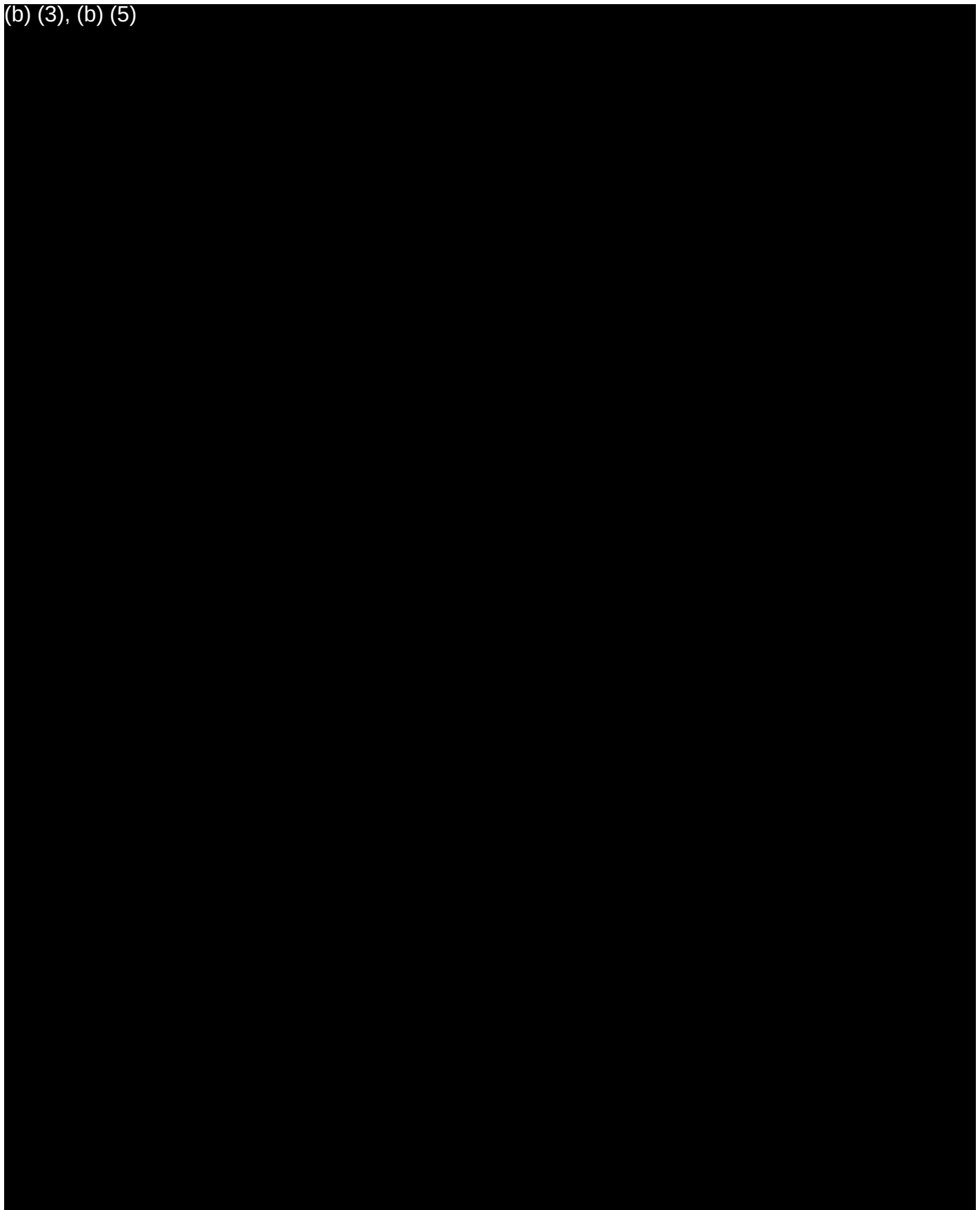
Orion Heat shield IRT Report

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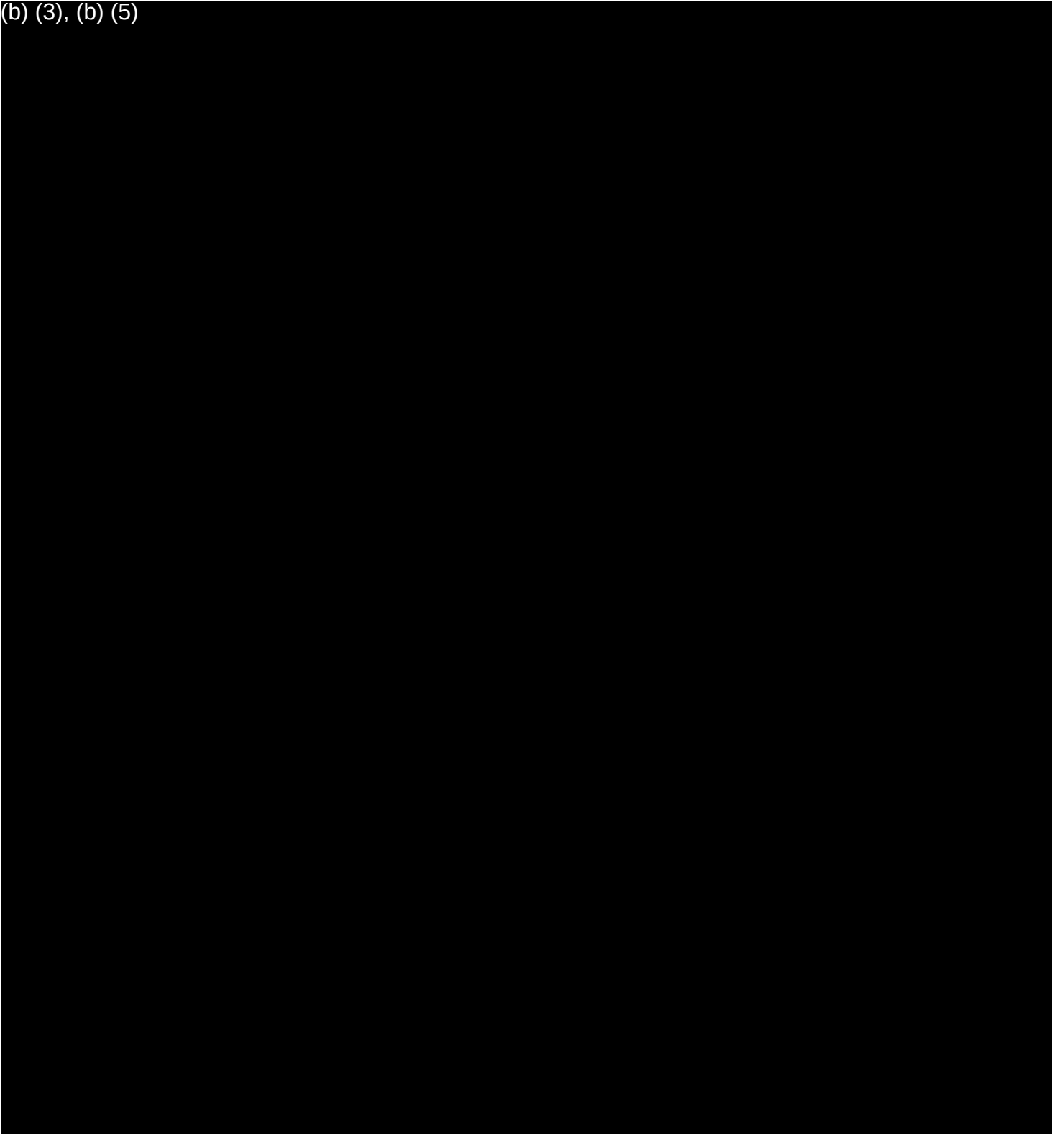
Orion Heat shield IRT Report

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Orion Heat shield IRT Report

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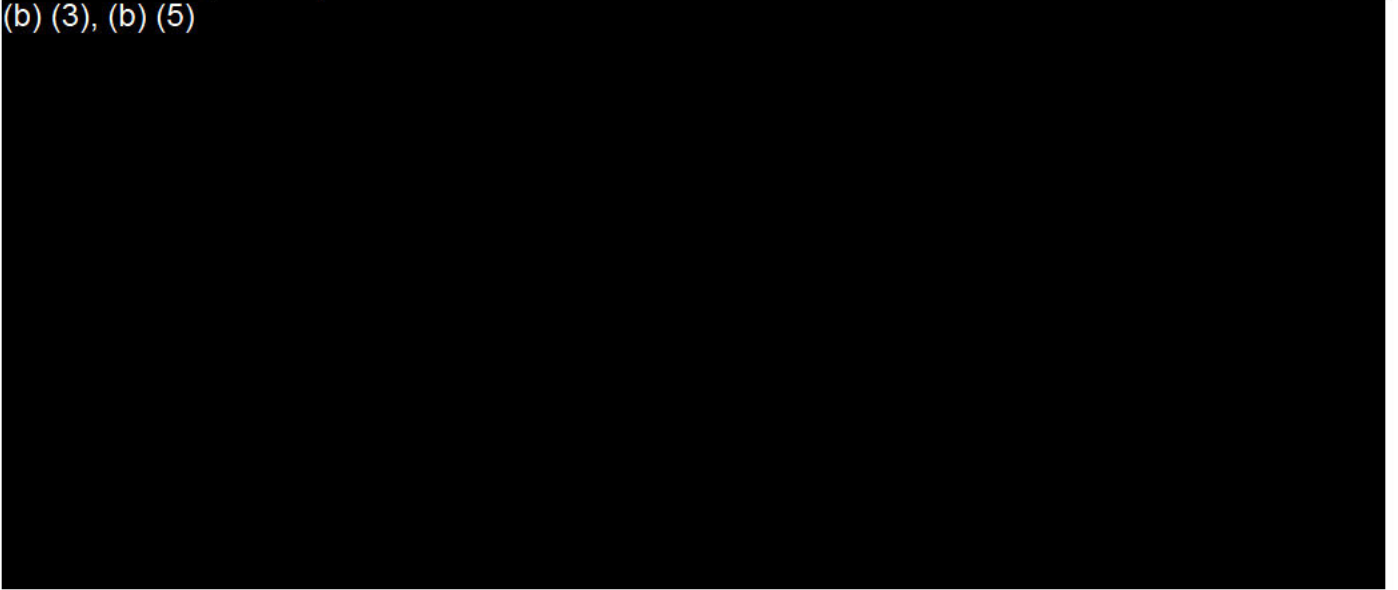


2.2 Root Cause and Corrective Actions

Observations and Recommendations

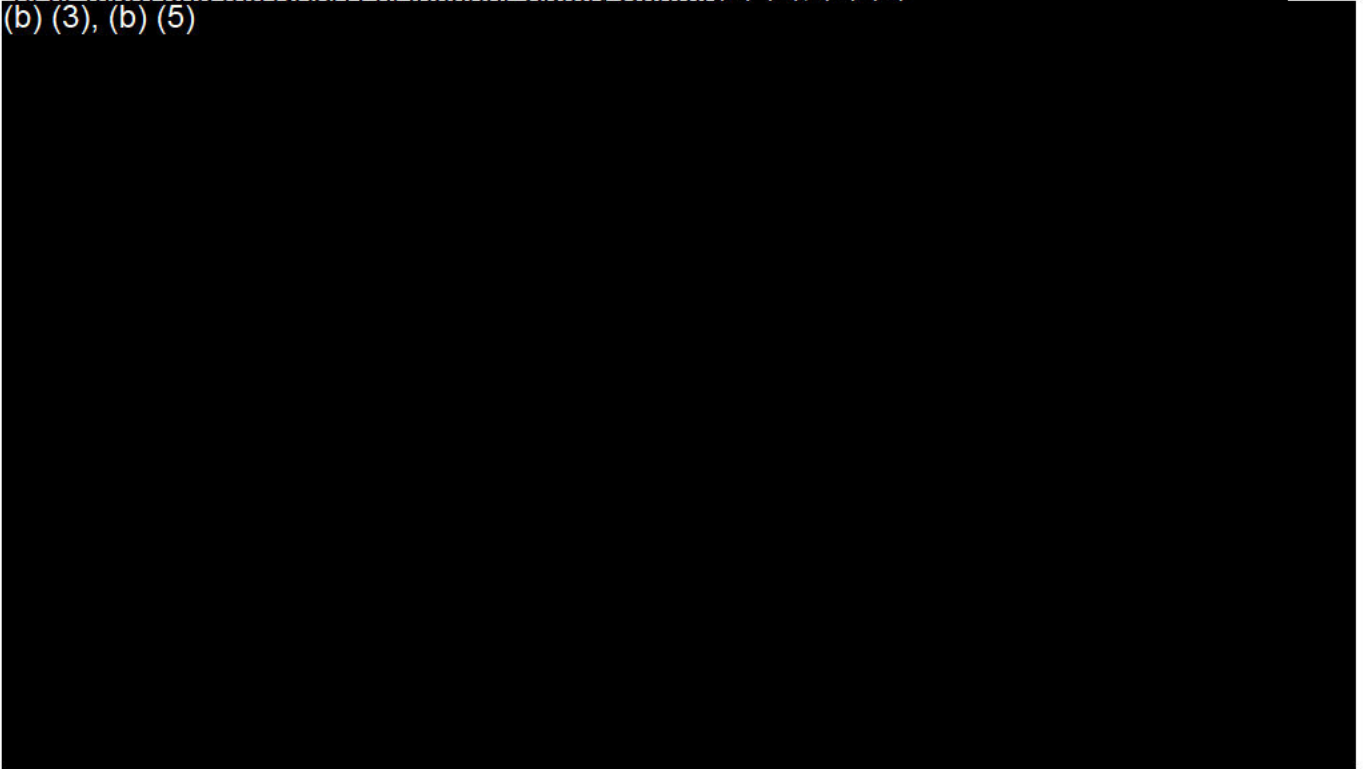
Questions posed by NASA:

(b) (3), (b) (5)



As part of the investigation into the root cause of char loss on Artemis I, the Heat Shield Tiger Team and the NASA Engineering Safety Center

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Orion Heat shield IRT Report

(b) (3), (b) (5)



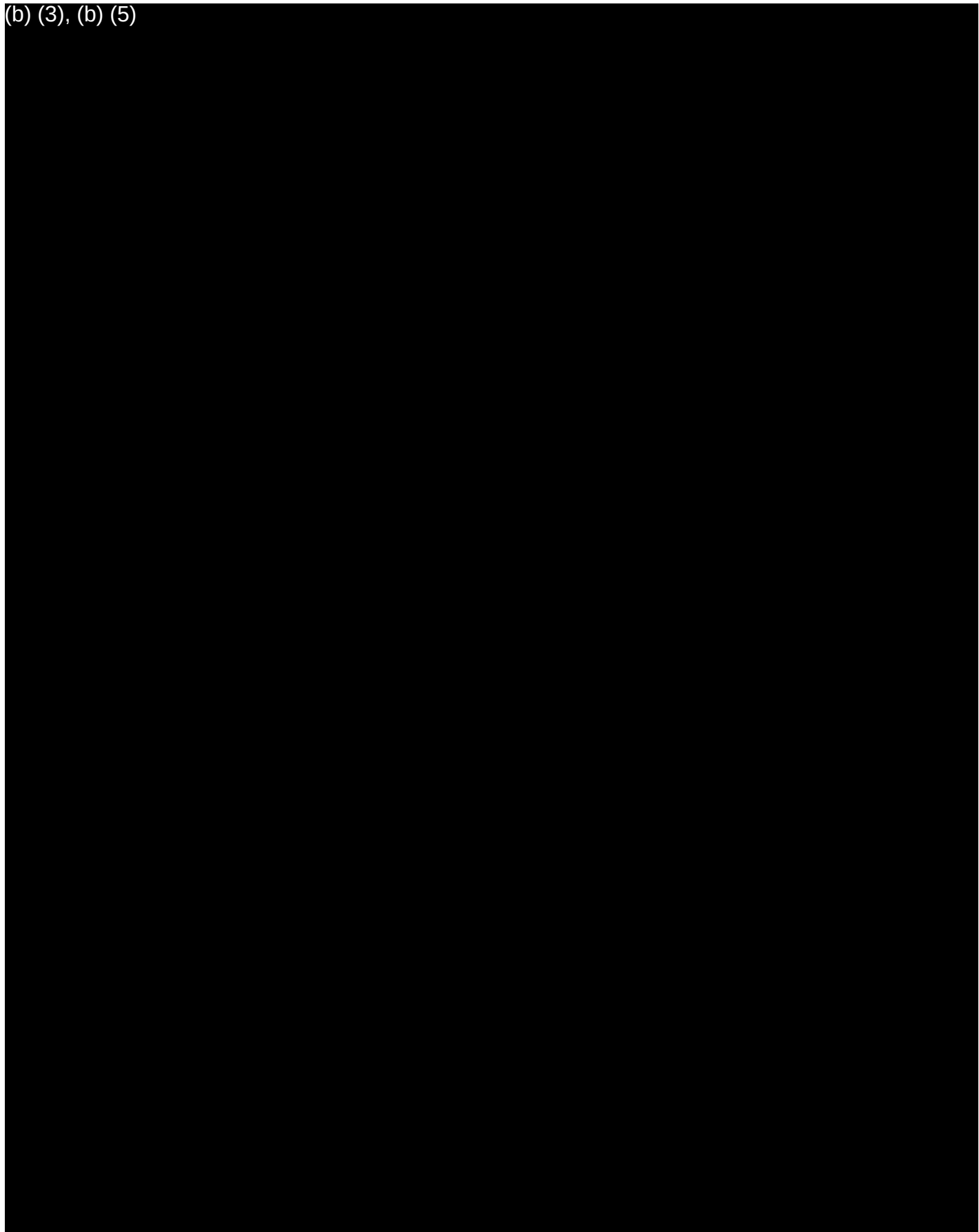
Artemis I Post-flight Analysis and Inspection

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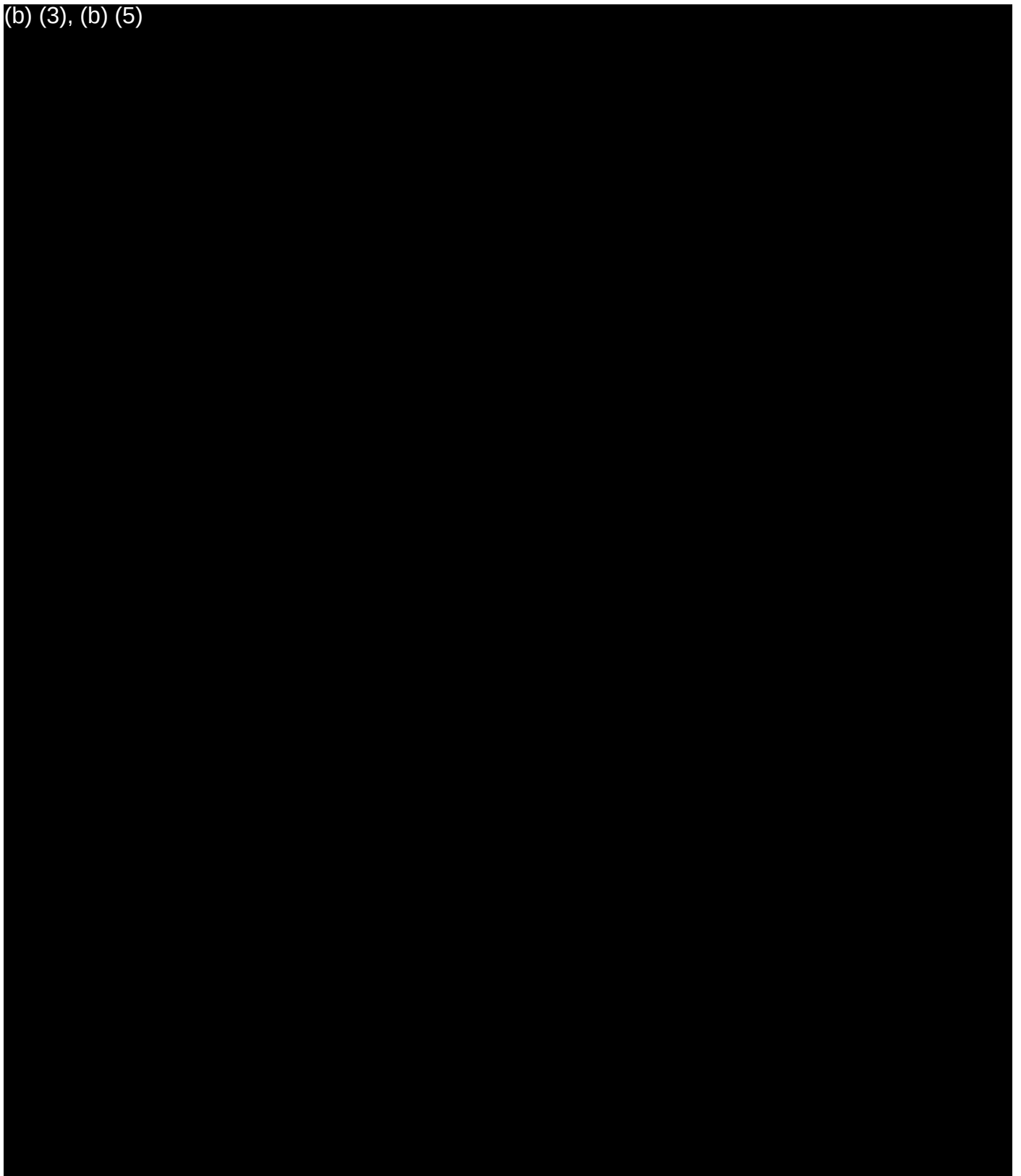
Orion Heat shield IRT Report

(b) (3), (b) (5)



Orion Heat shield IRT Report

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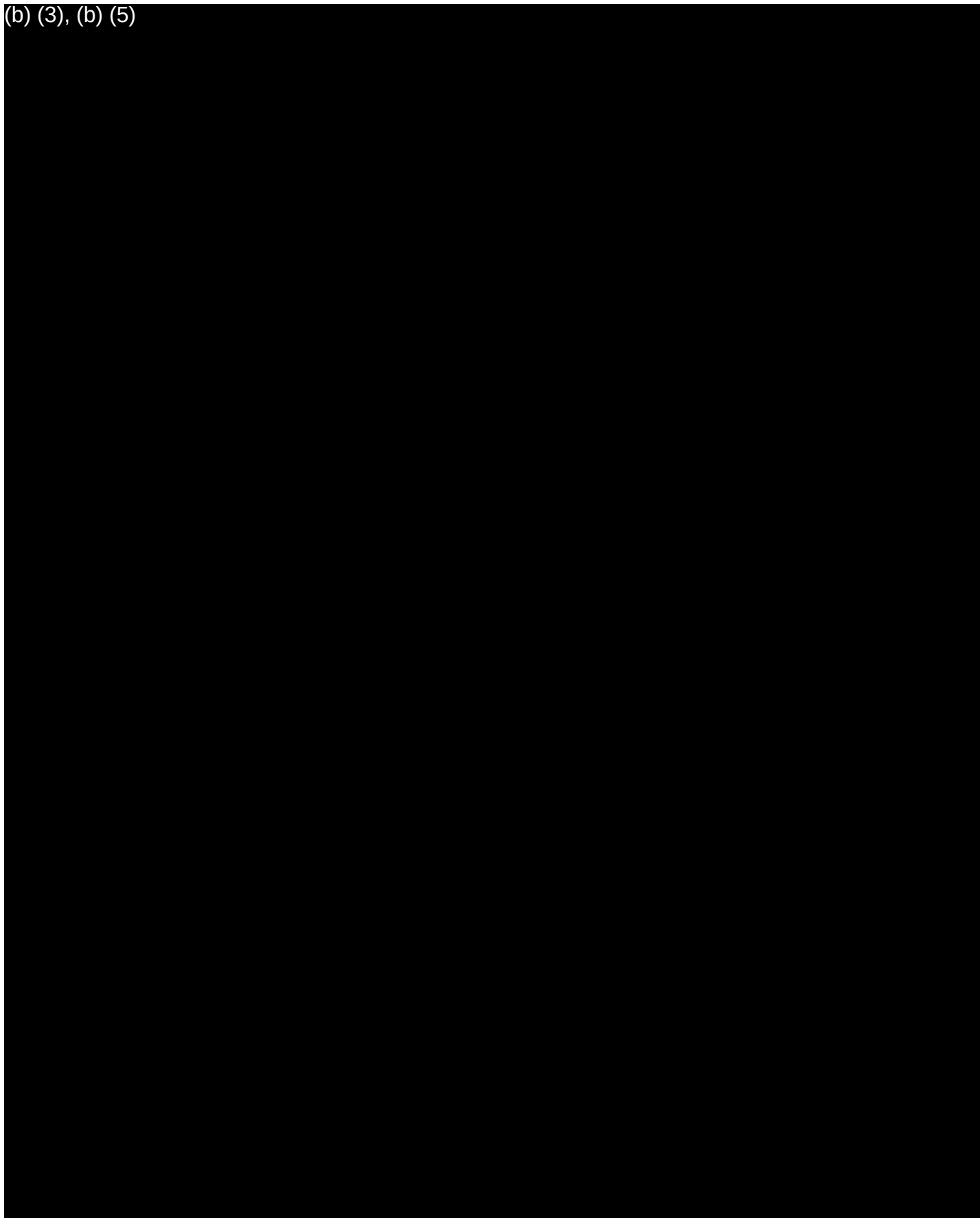
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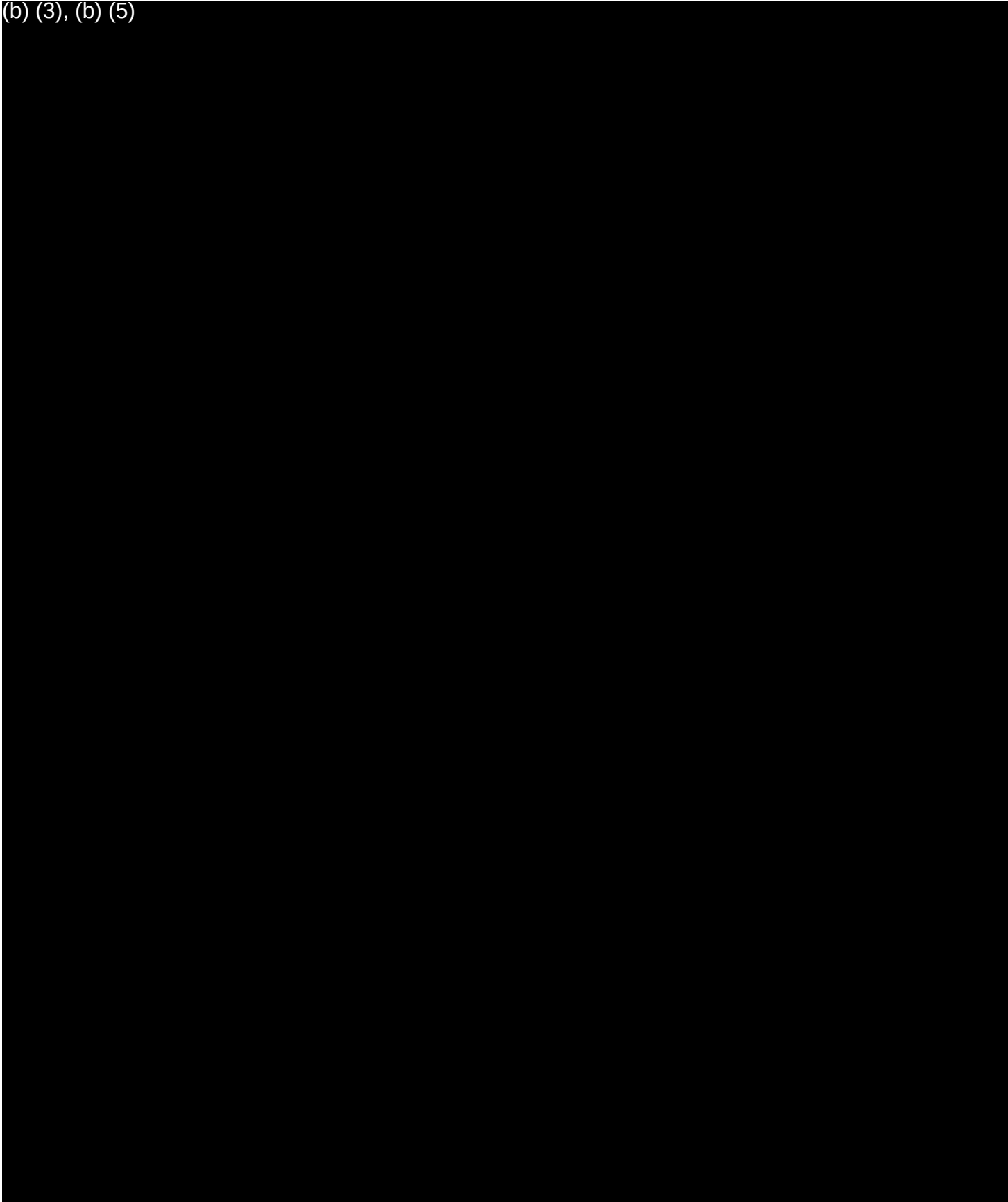


Orion Heat shield IRT Report

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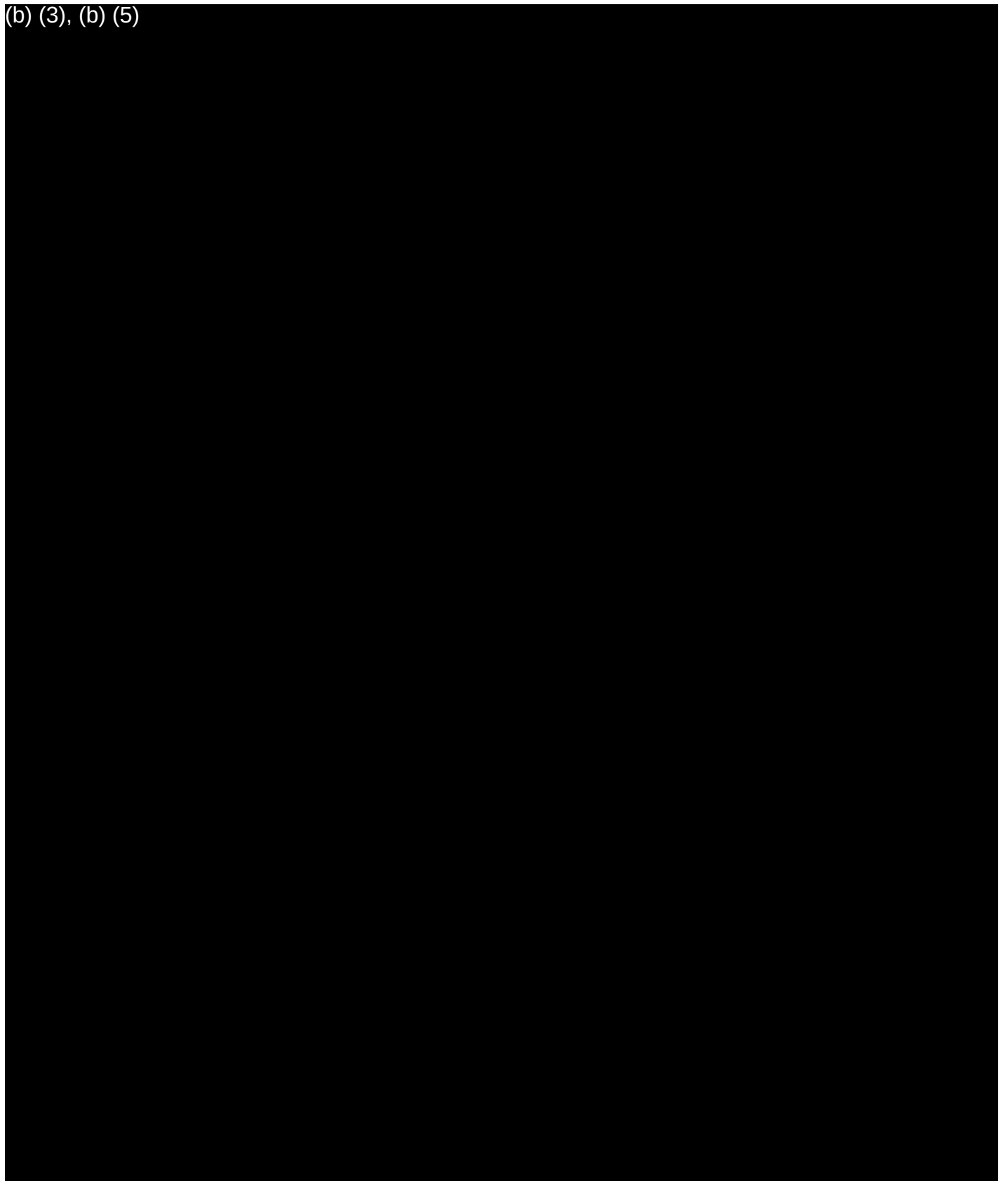


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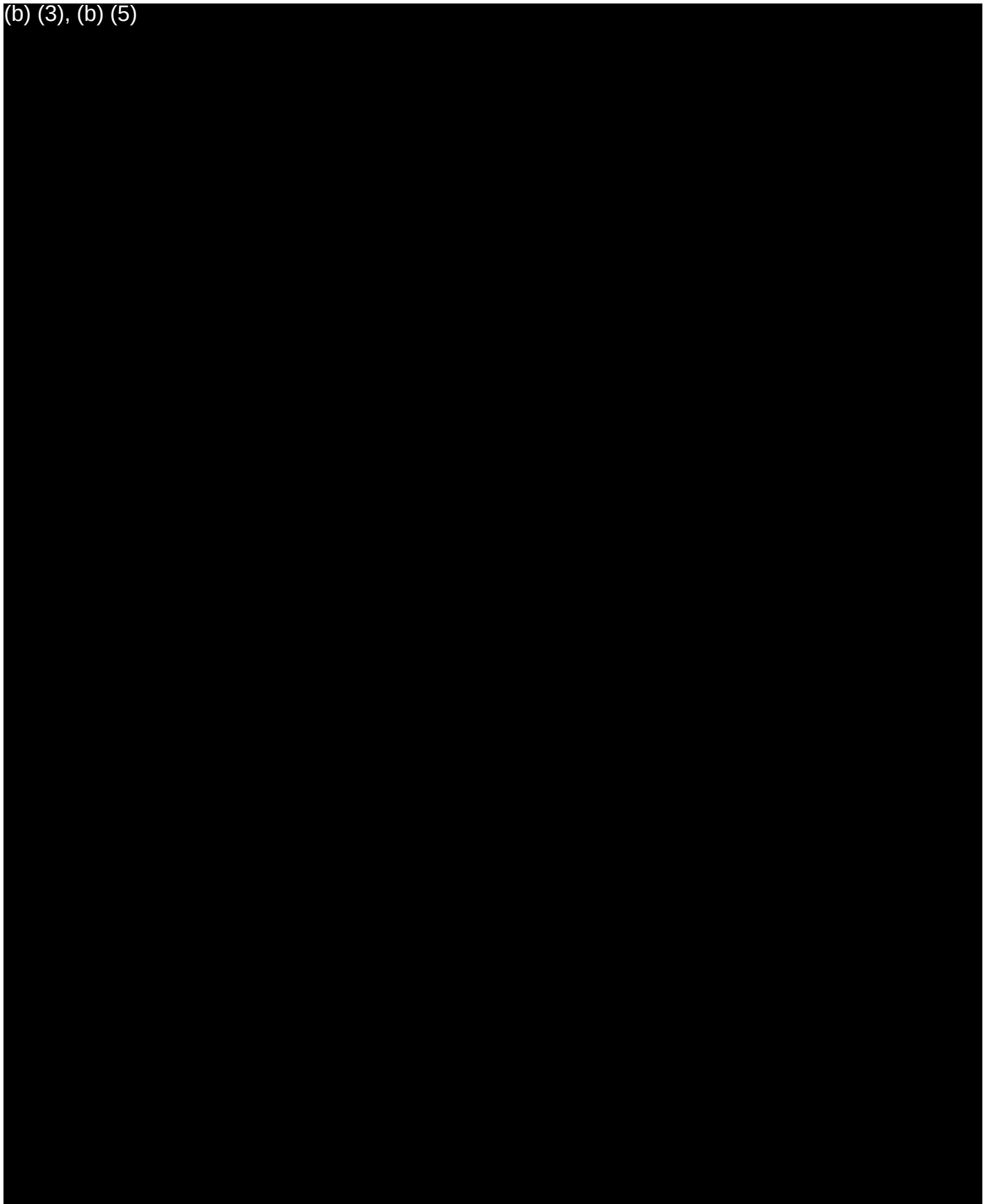
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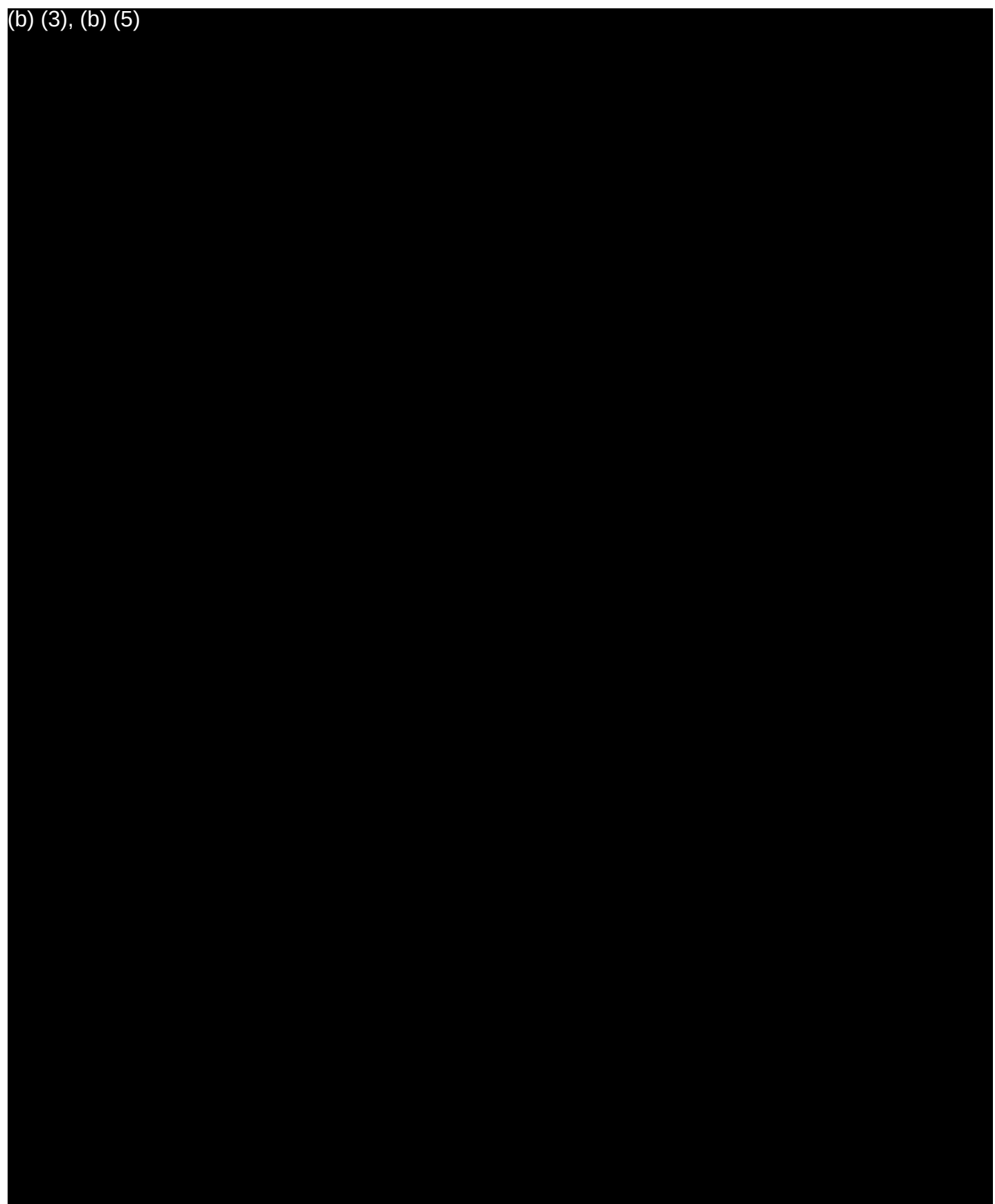


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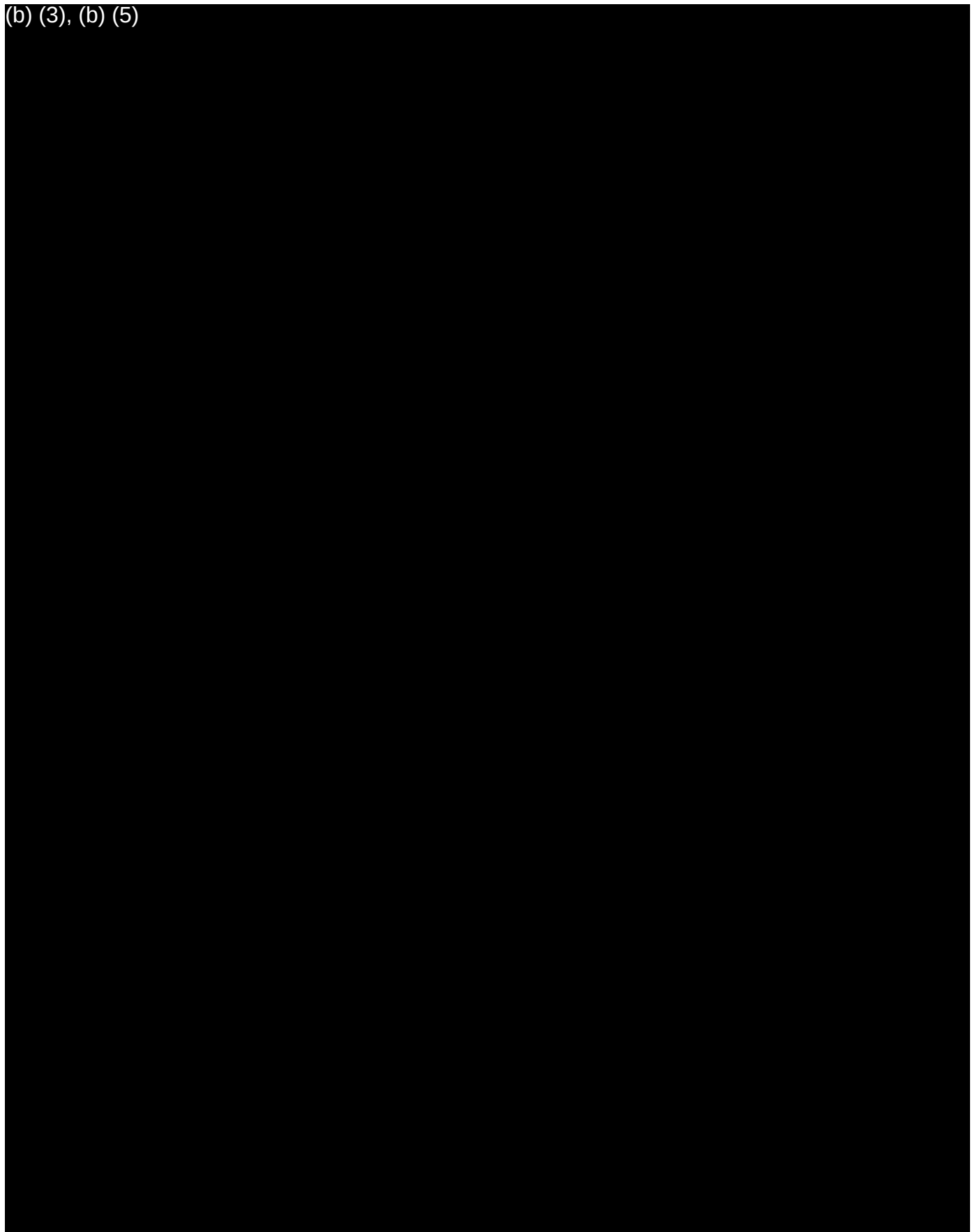


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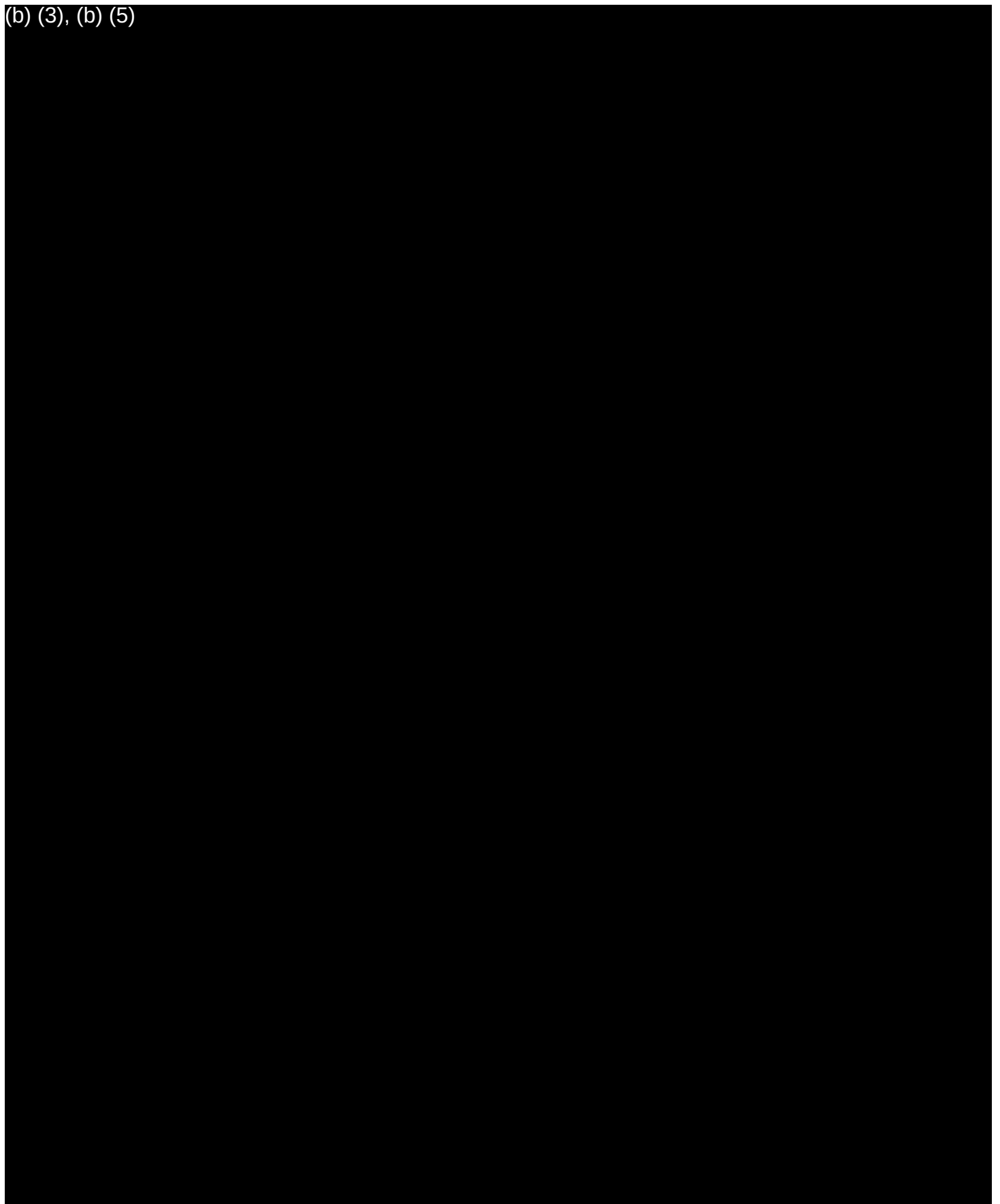
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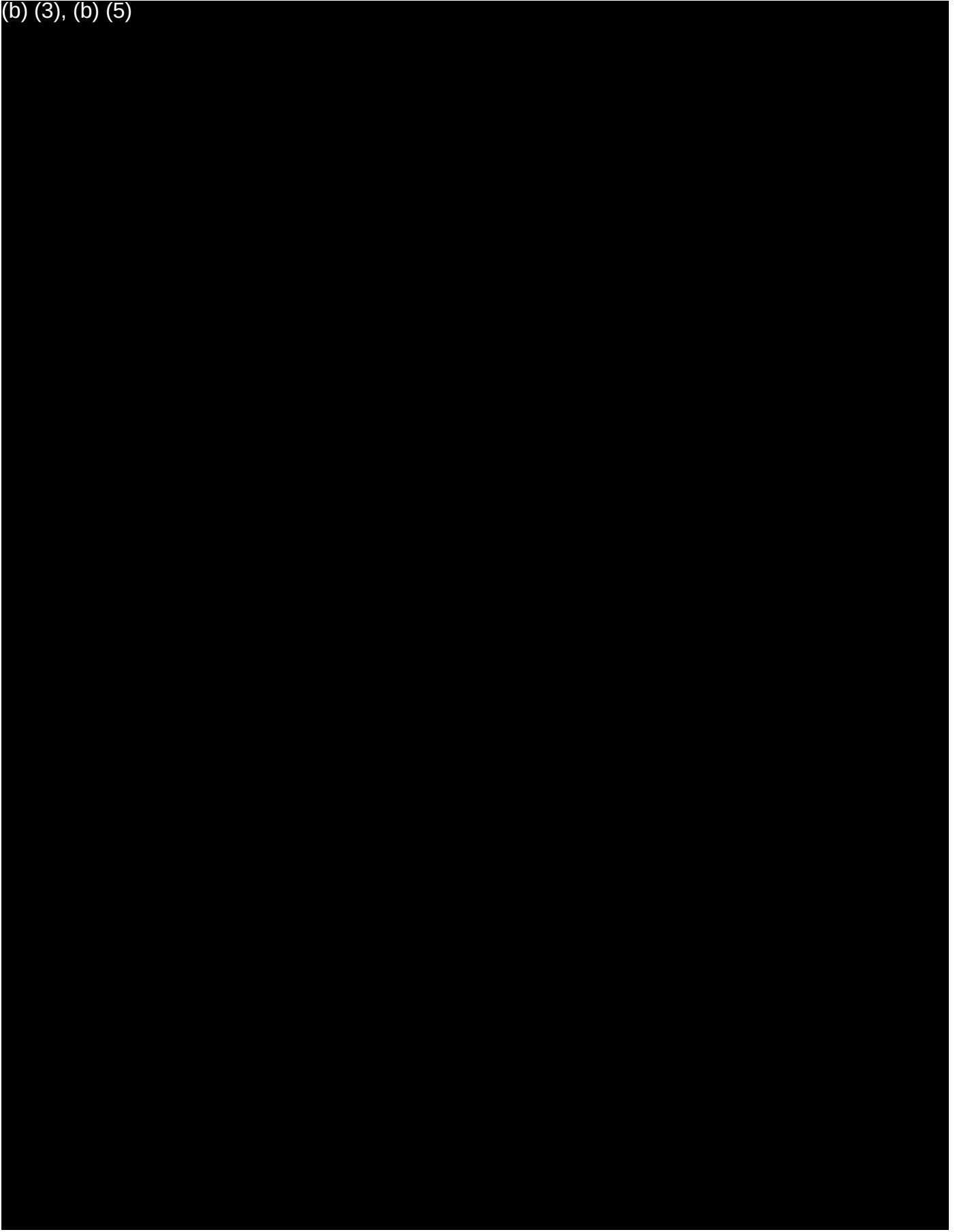
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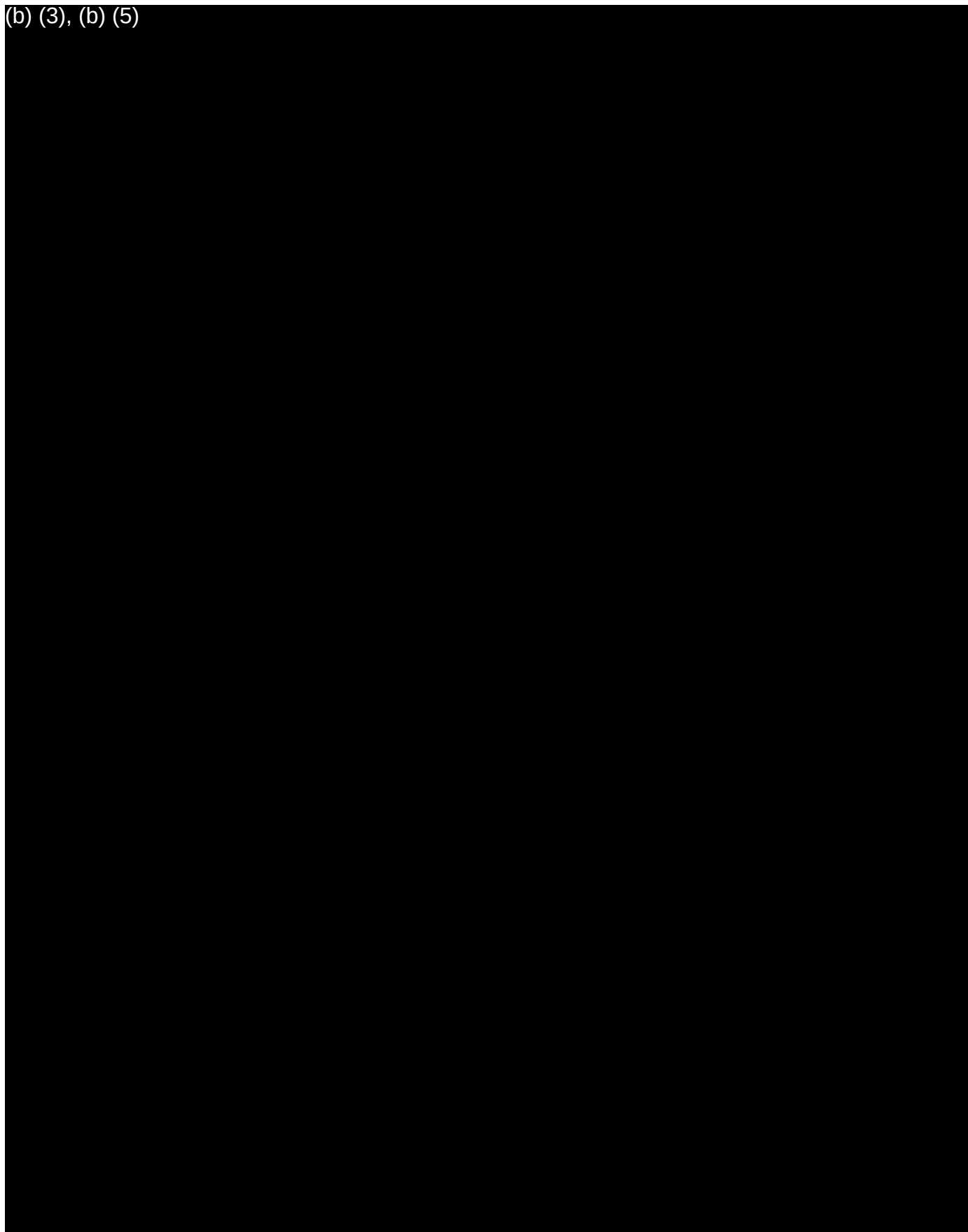
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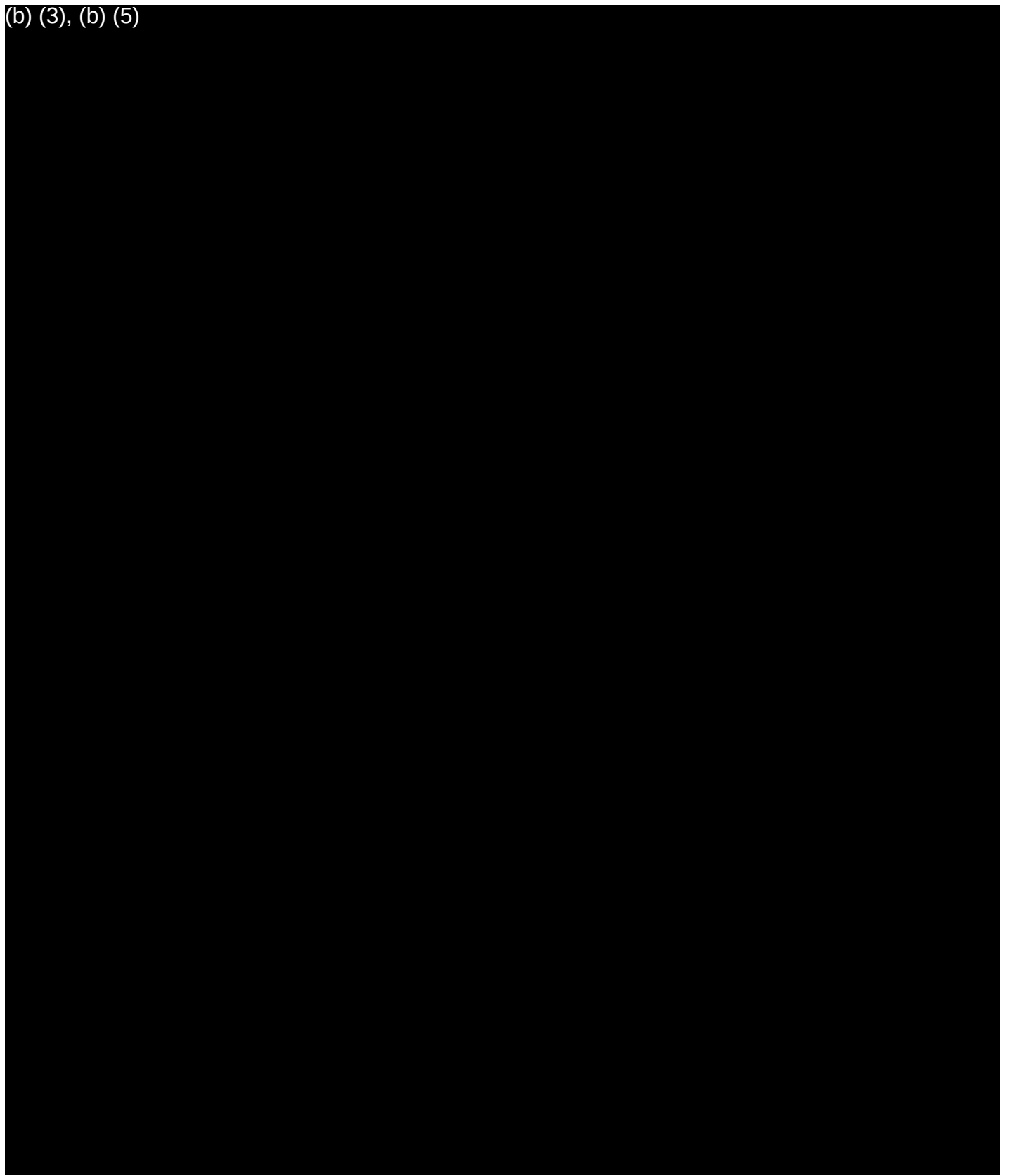
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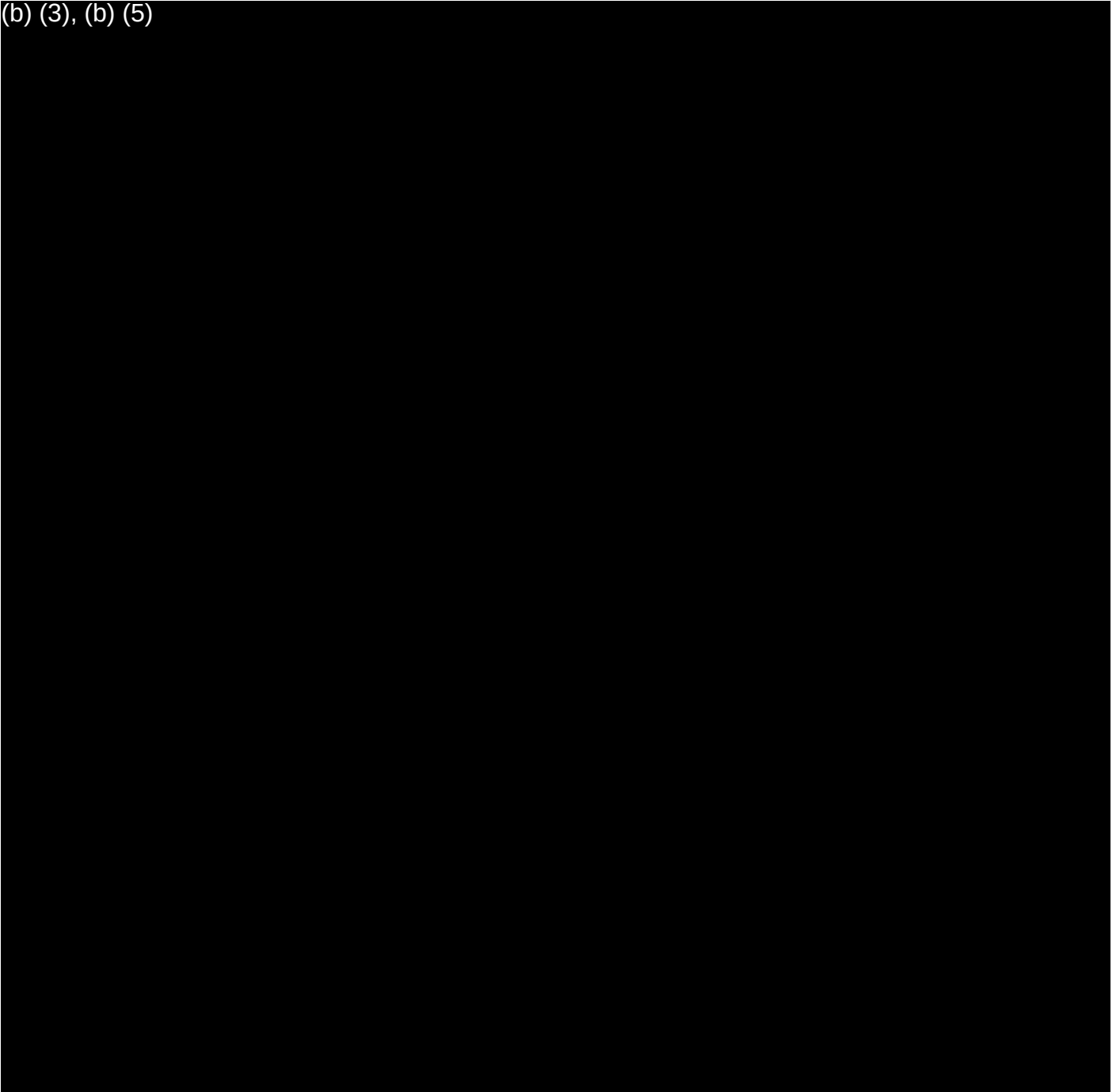
Orion Heat shield IRT Report

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Orion Heat shield IRT Report

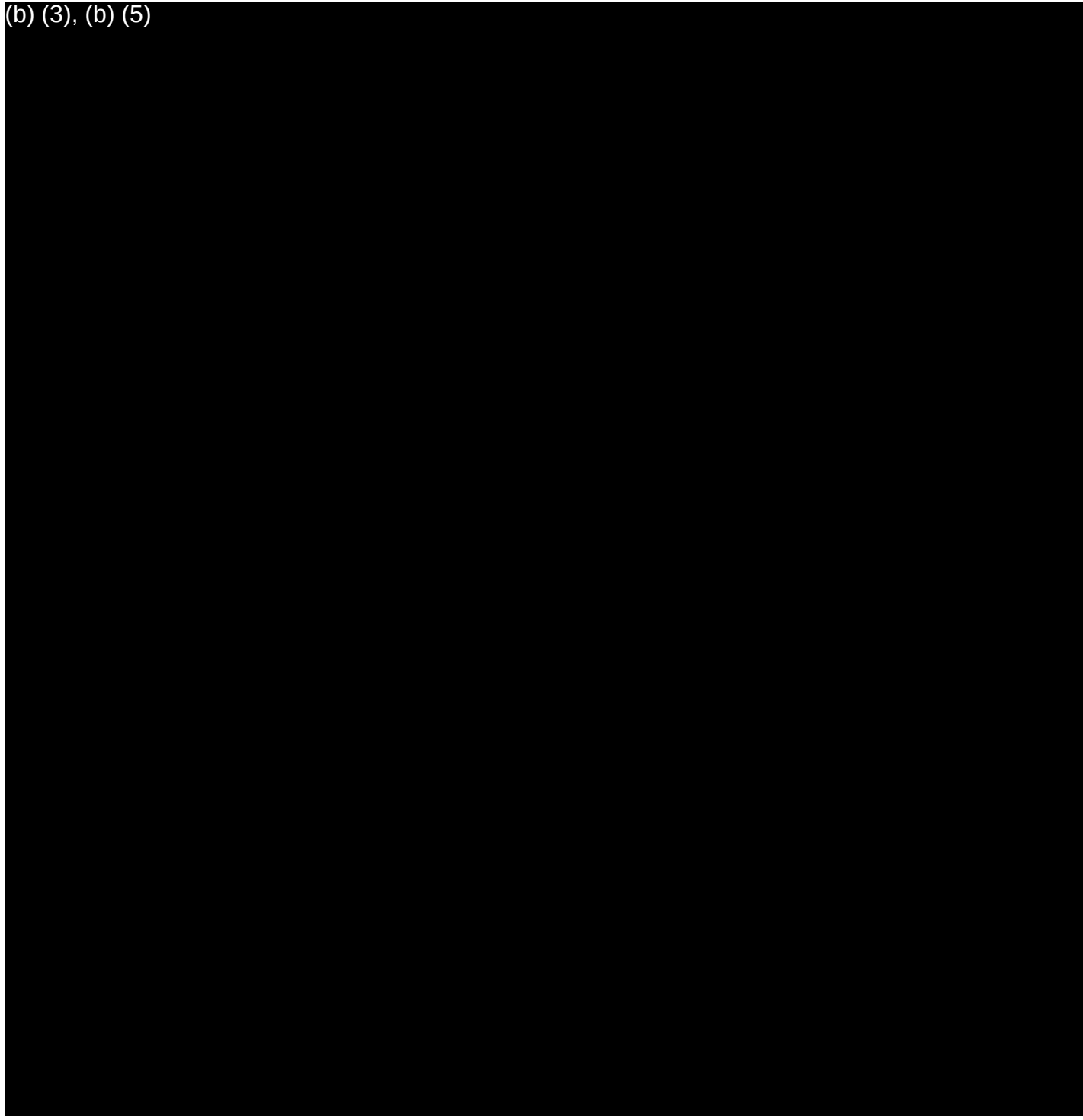
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2.3 Artemis II Heat Shield Flight Rationale Observations and Recommendations

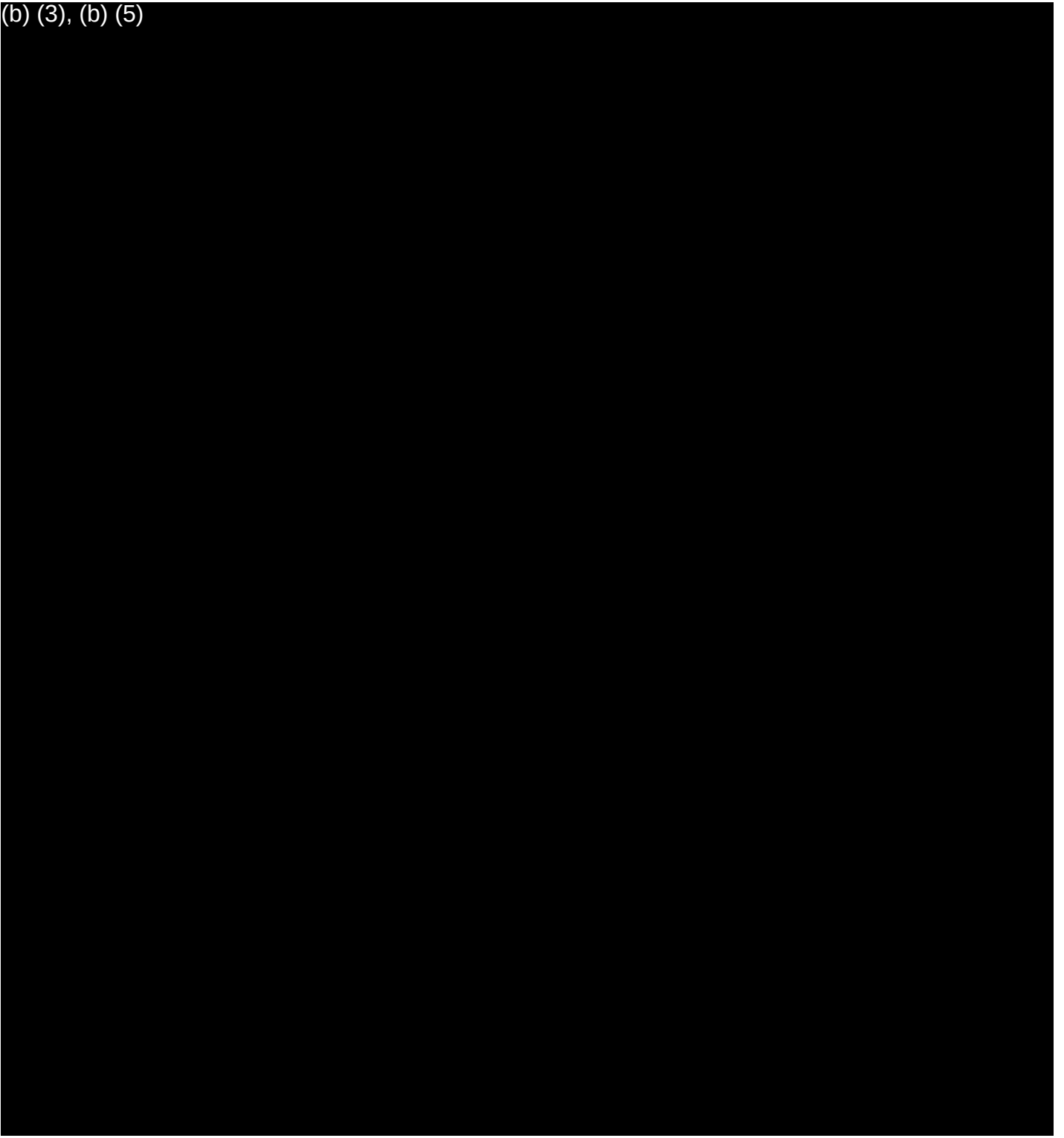
Questions posed by NASA:

(b) (3), (b) (5)



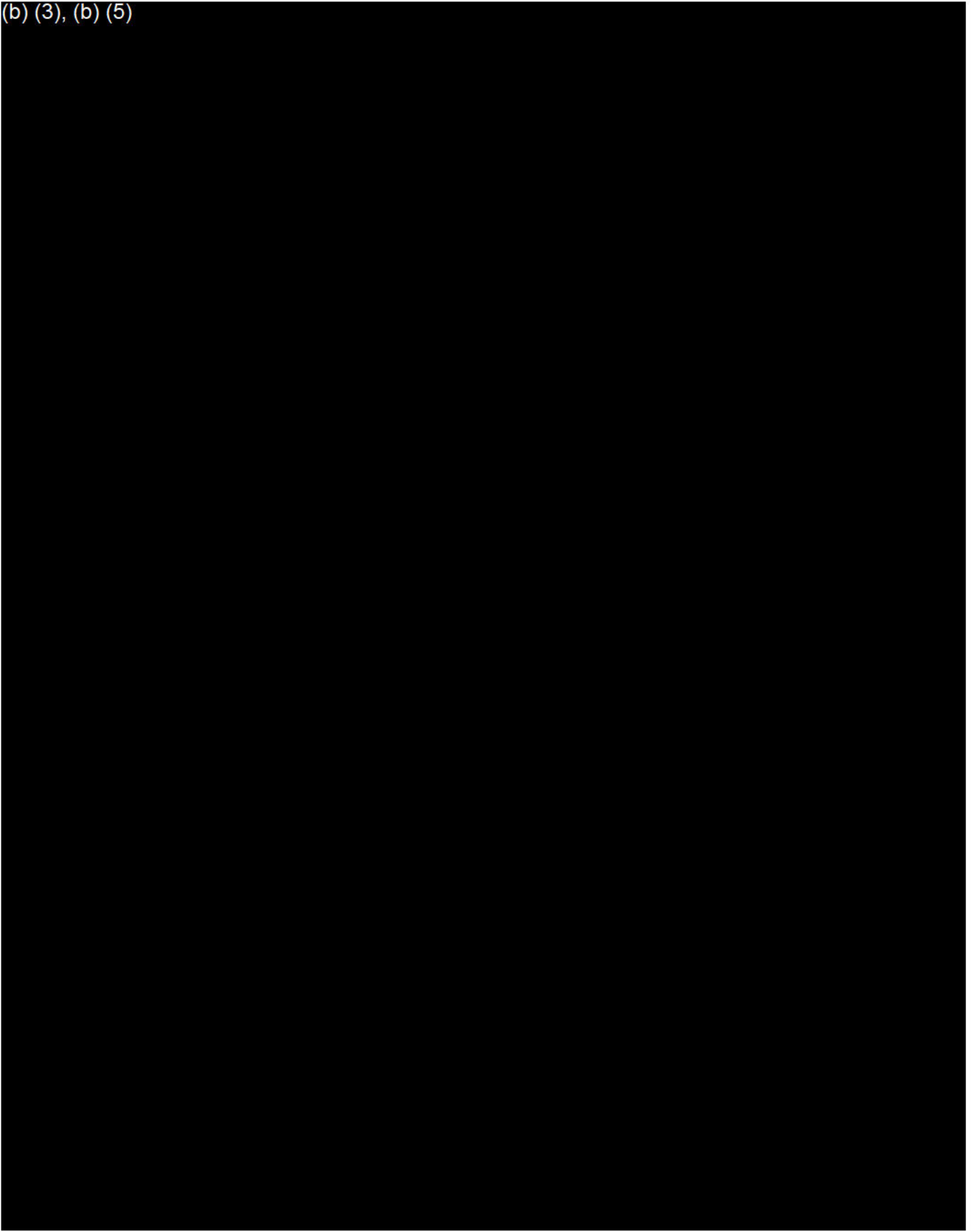
Orion Heat shield IRT Report

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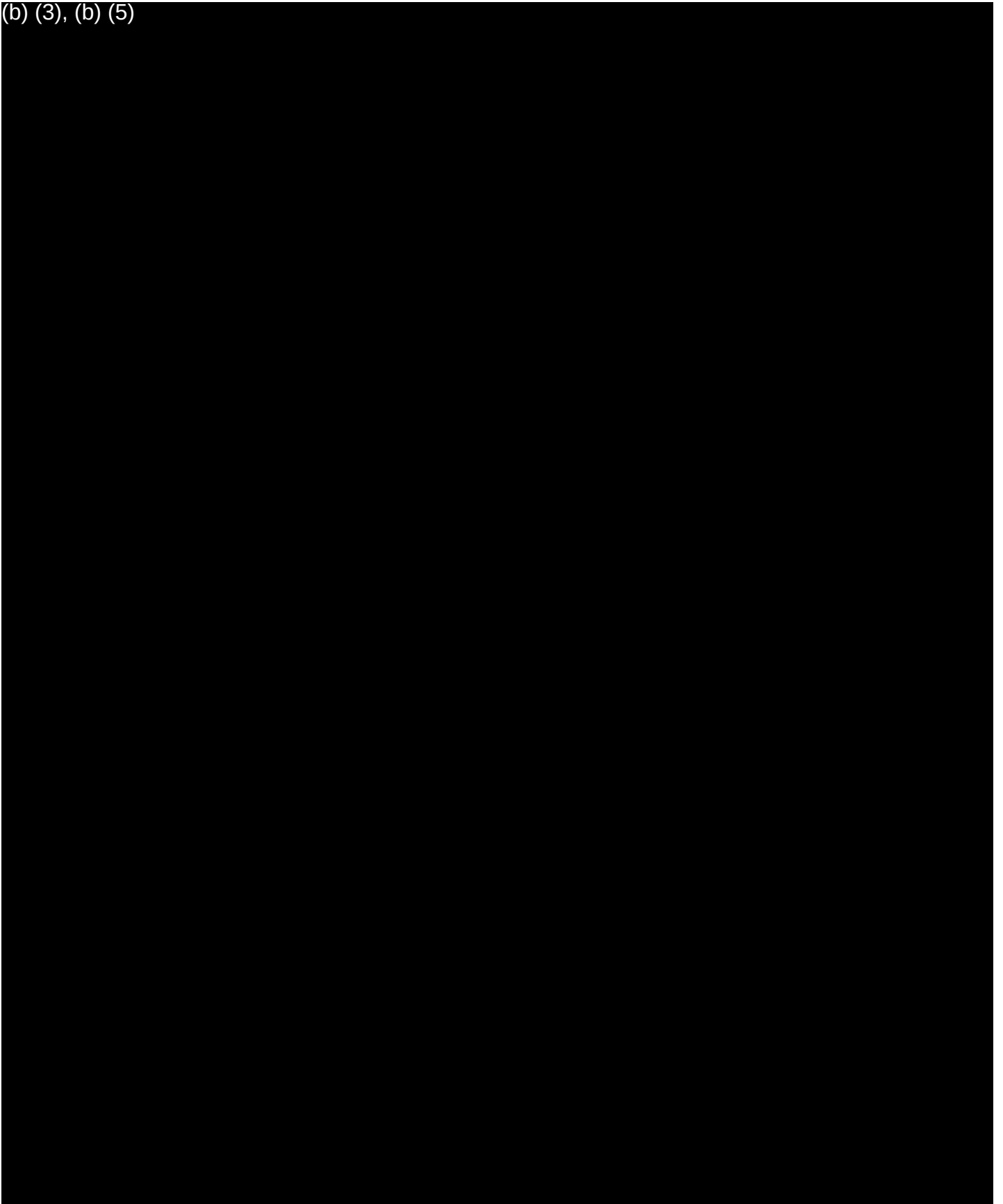


Orion Heat shield IRT Report

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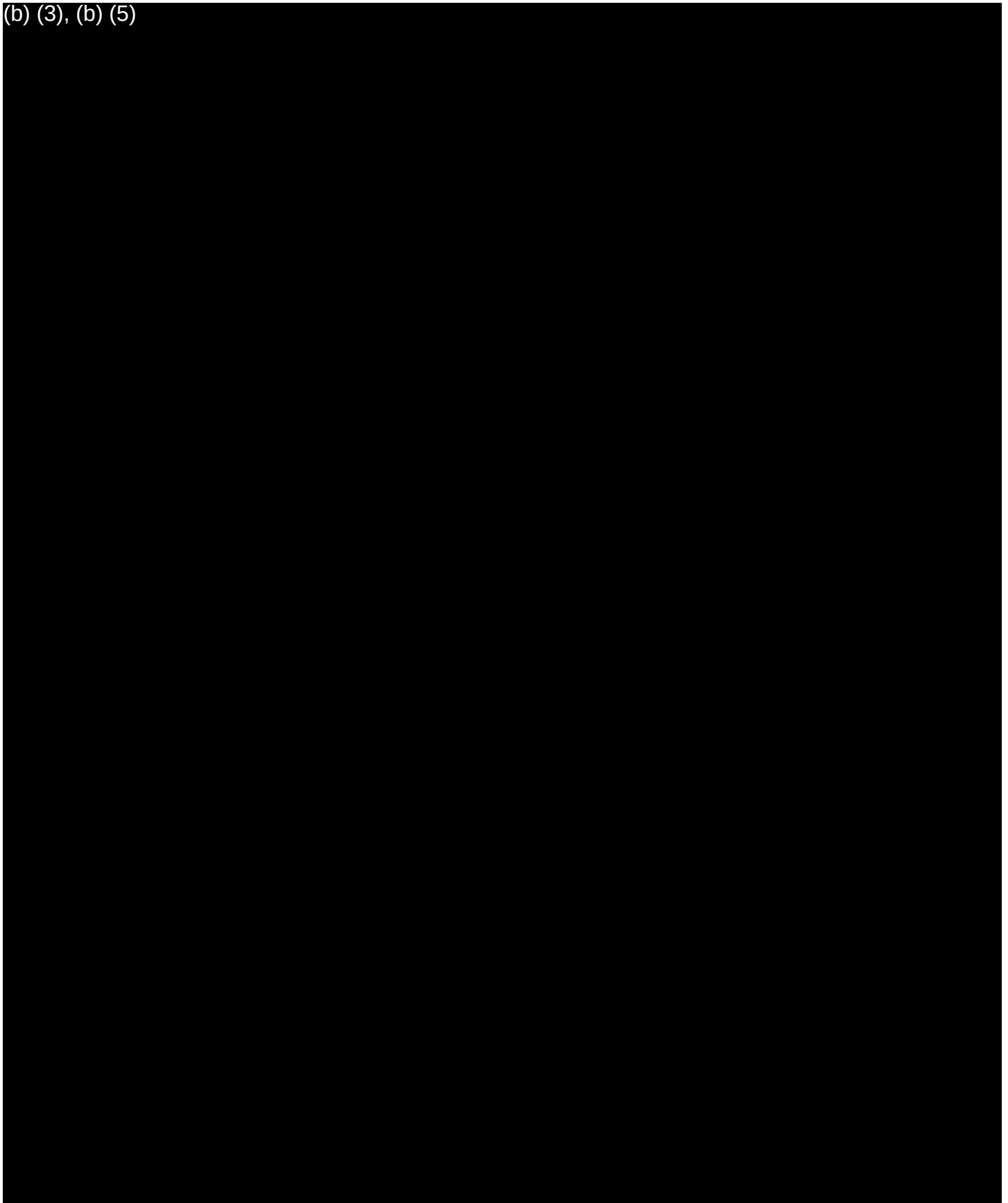


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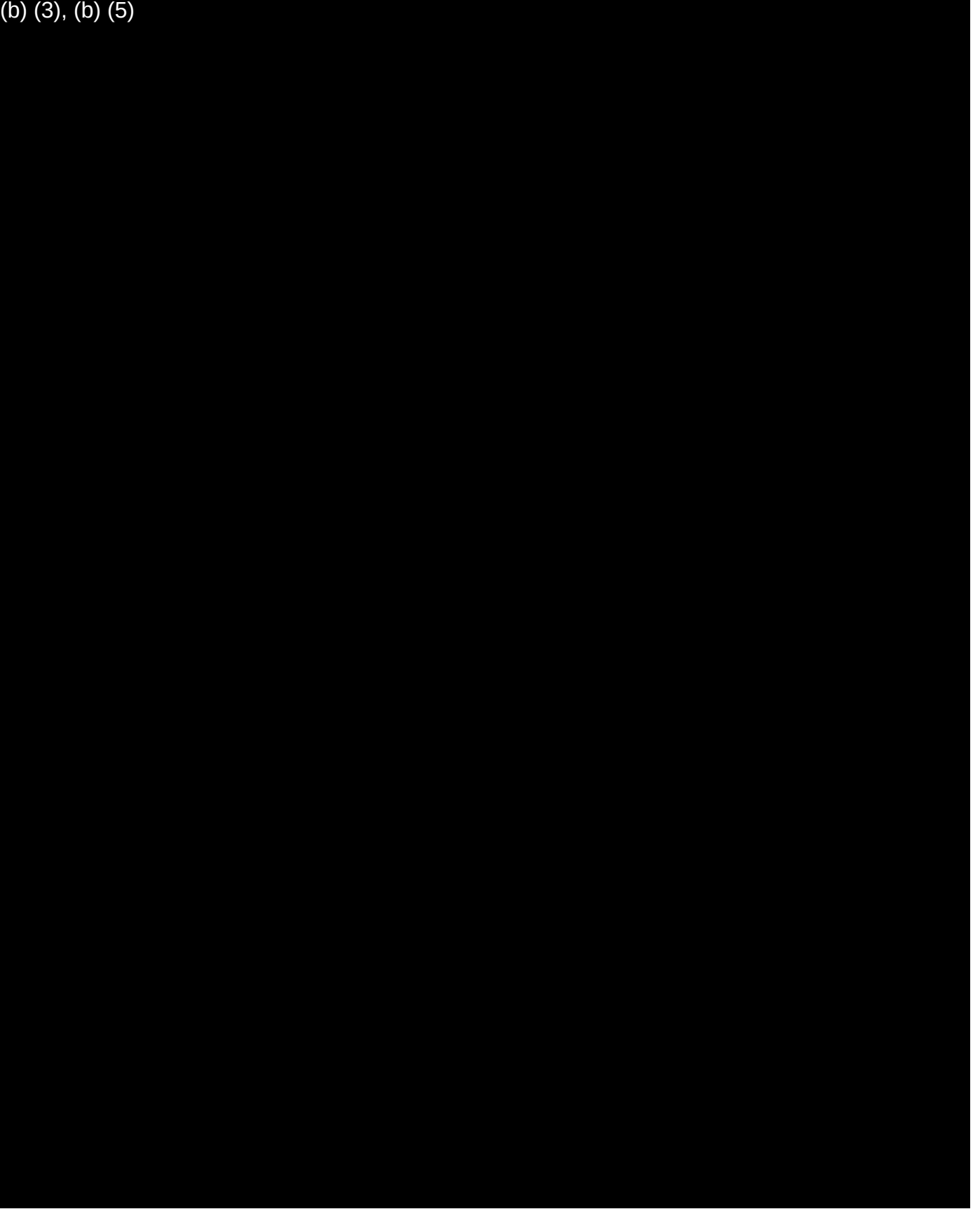
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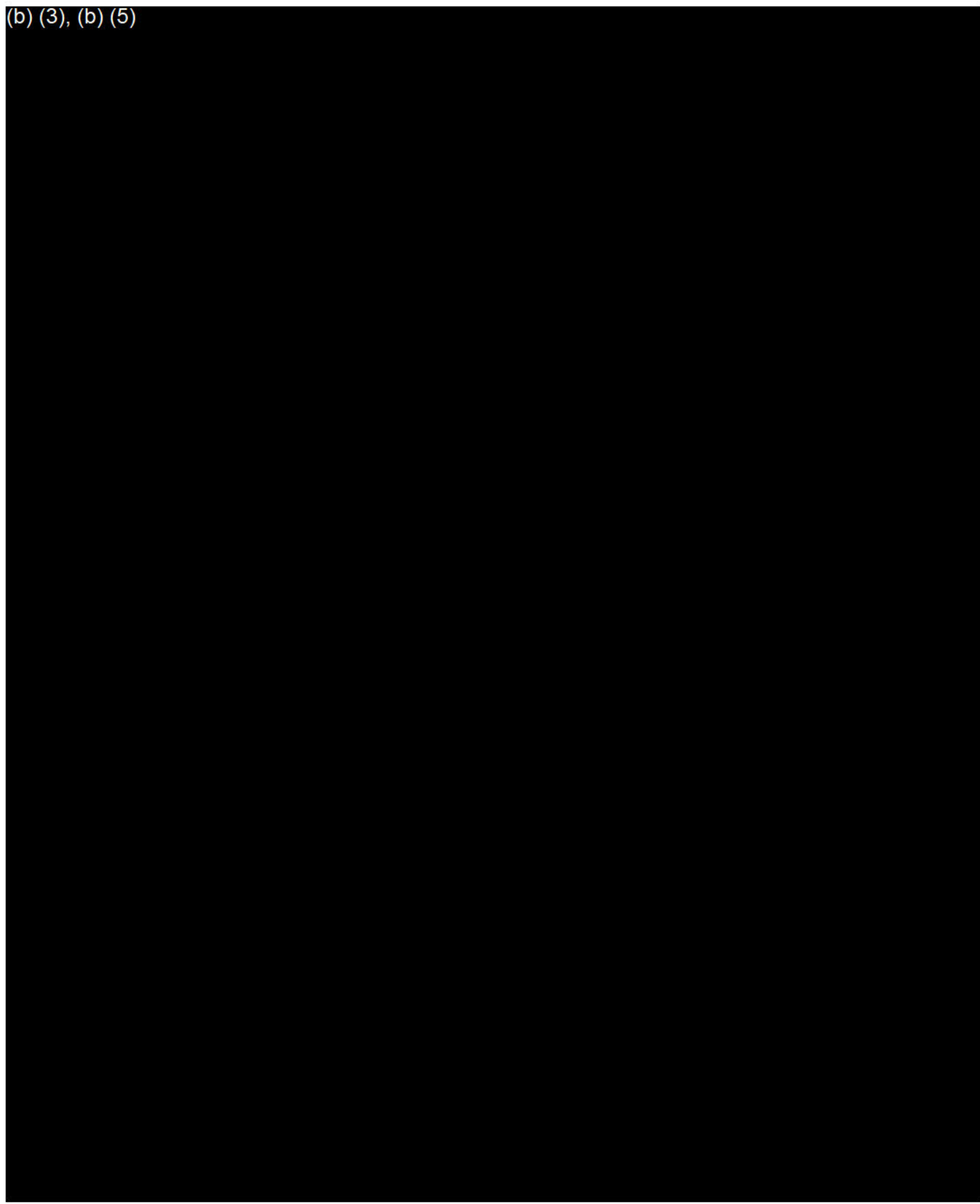
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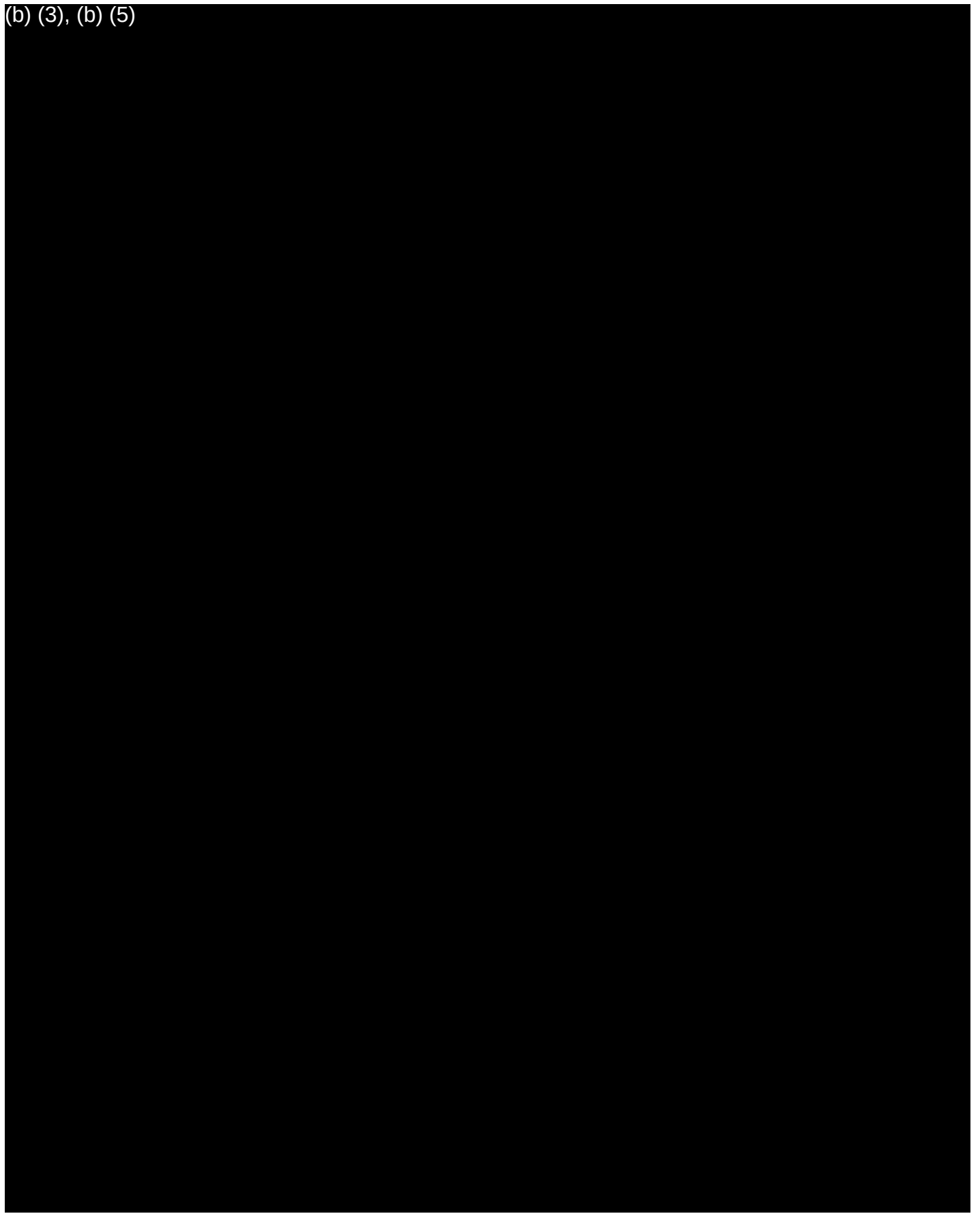


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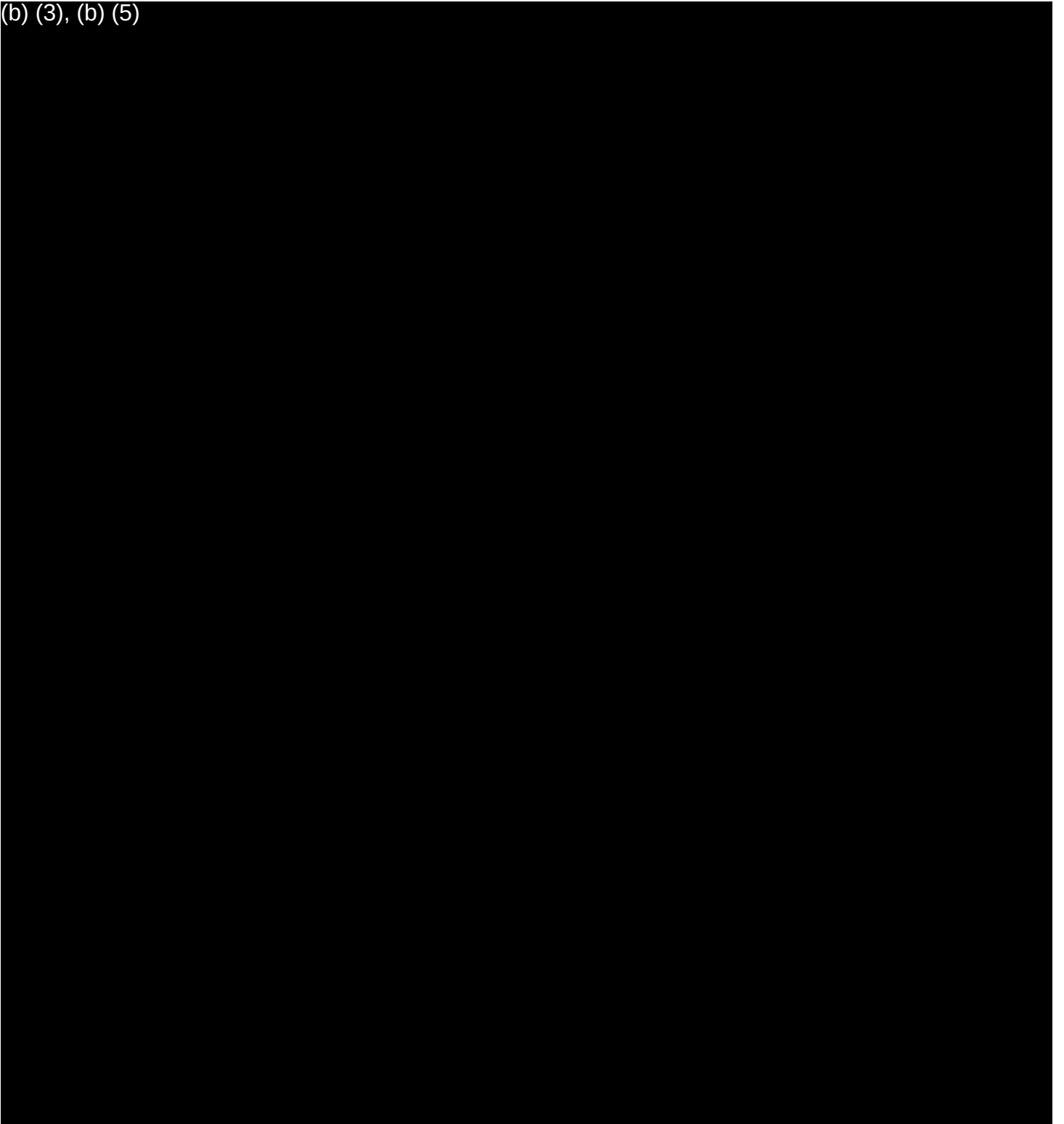
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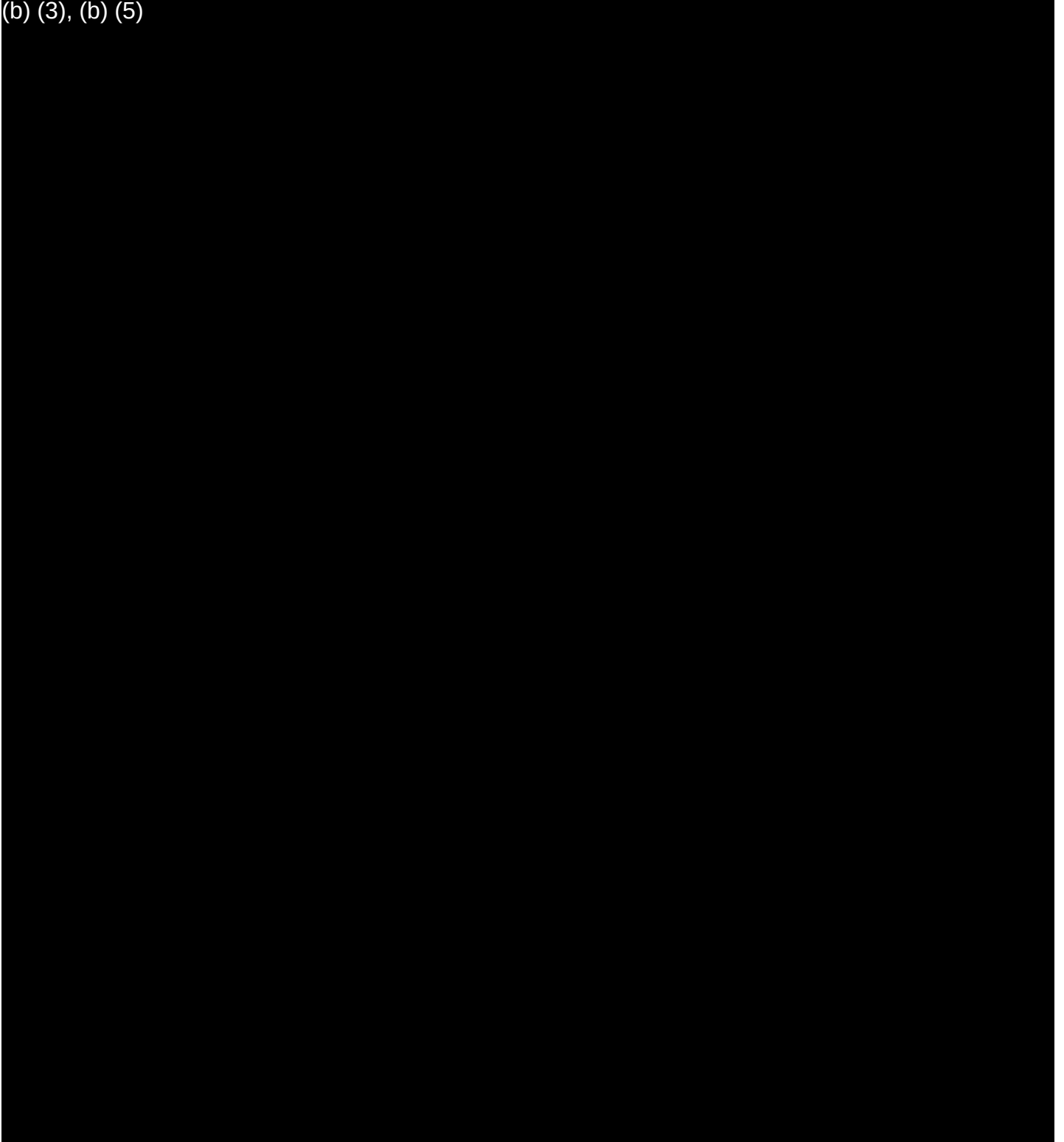
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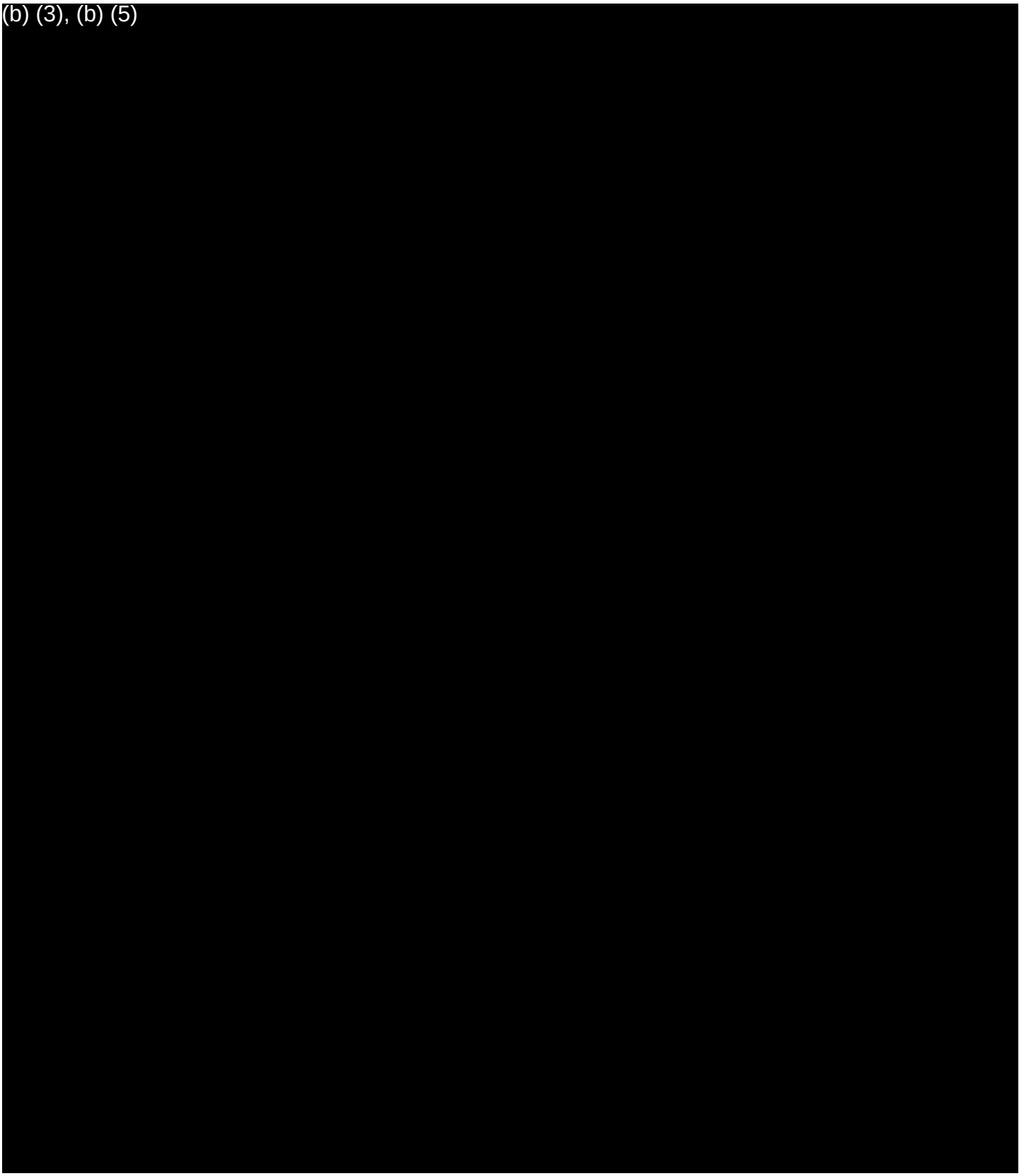
2.4 Remaining Concerns and Uncertainties

Questions posed by NASA:

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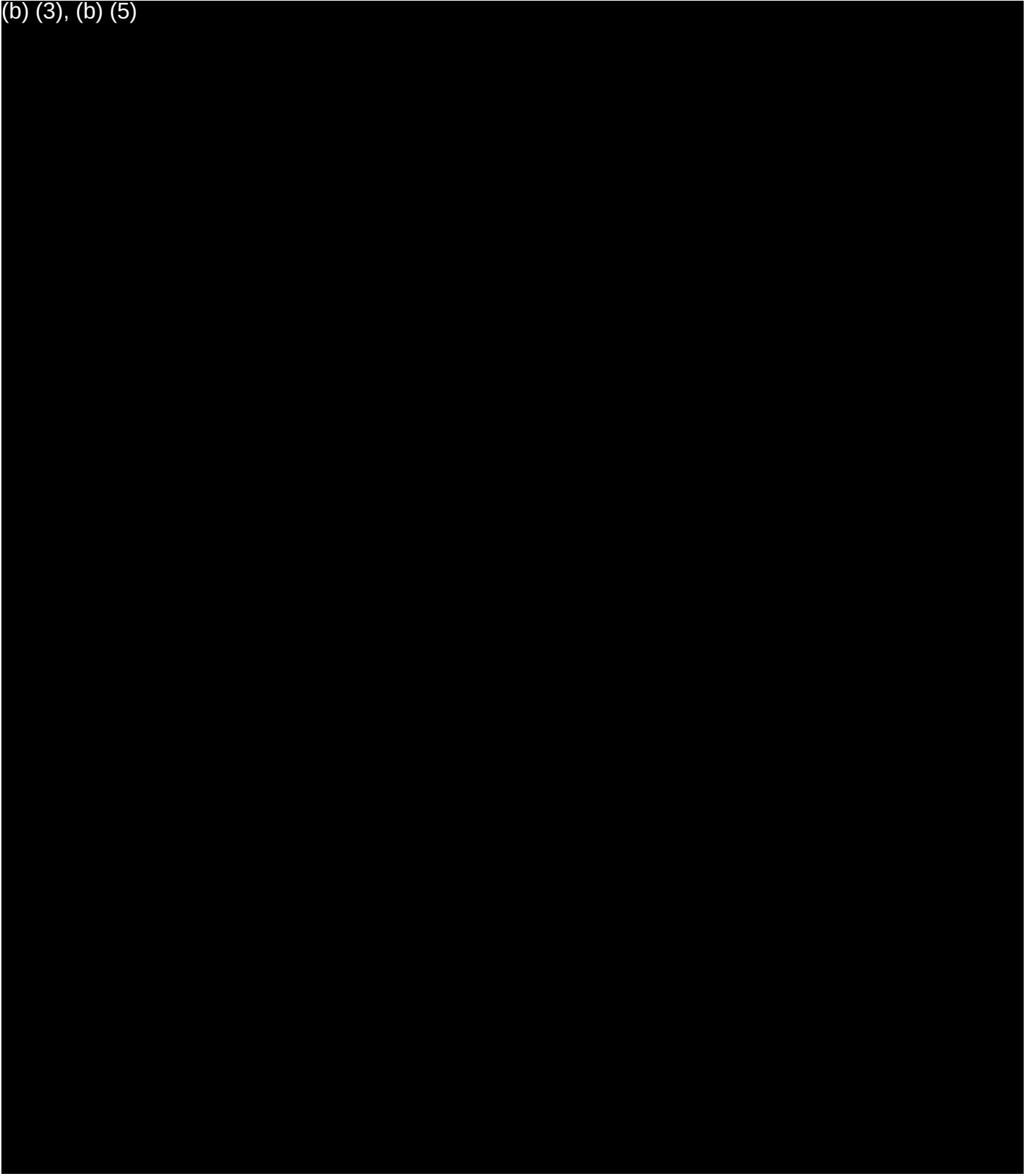


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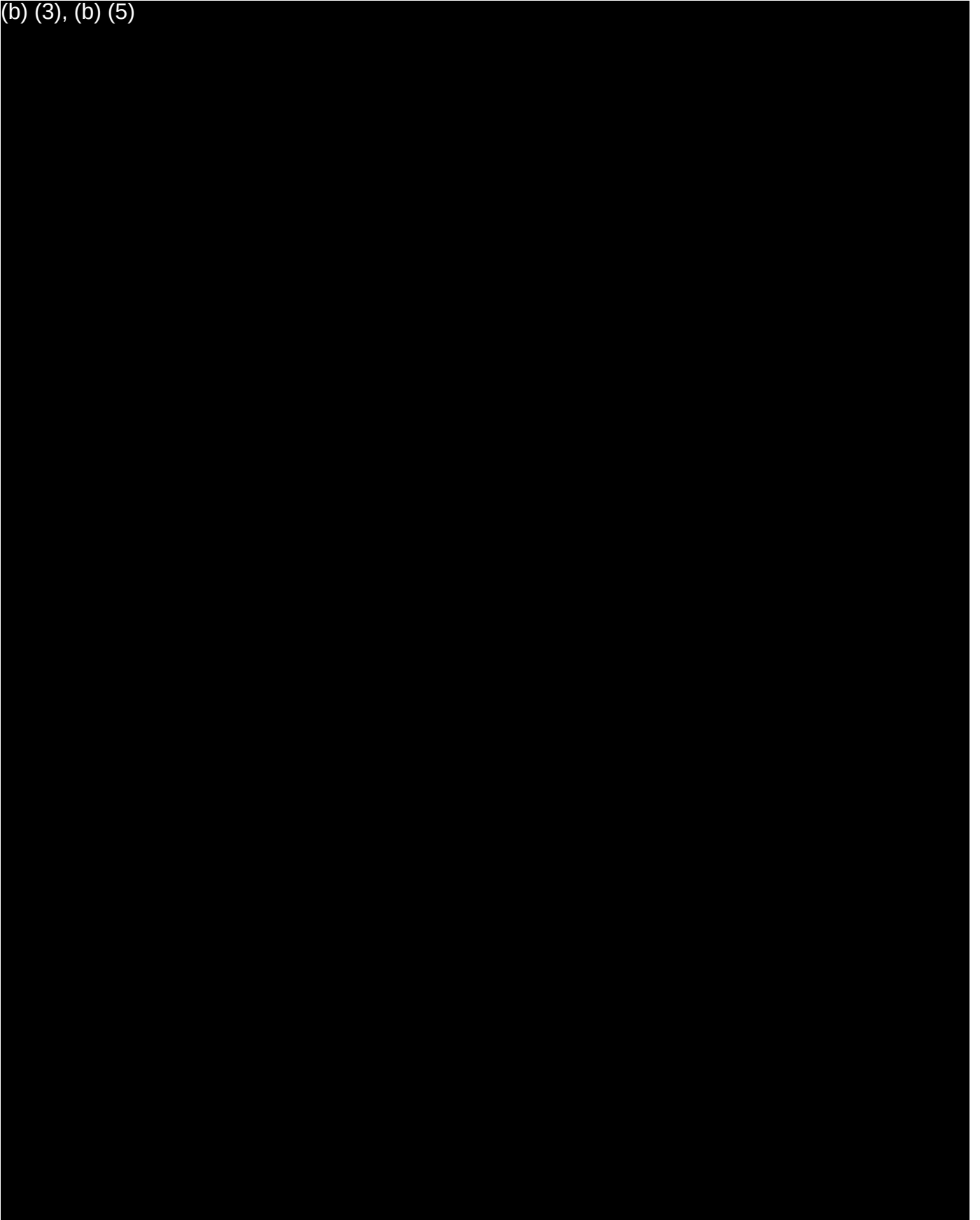
Orion Heat shield IRT Report

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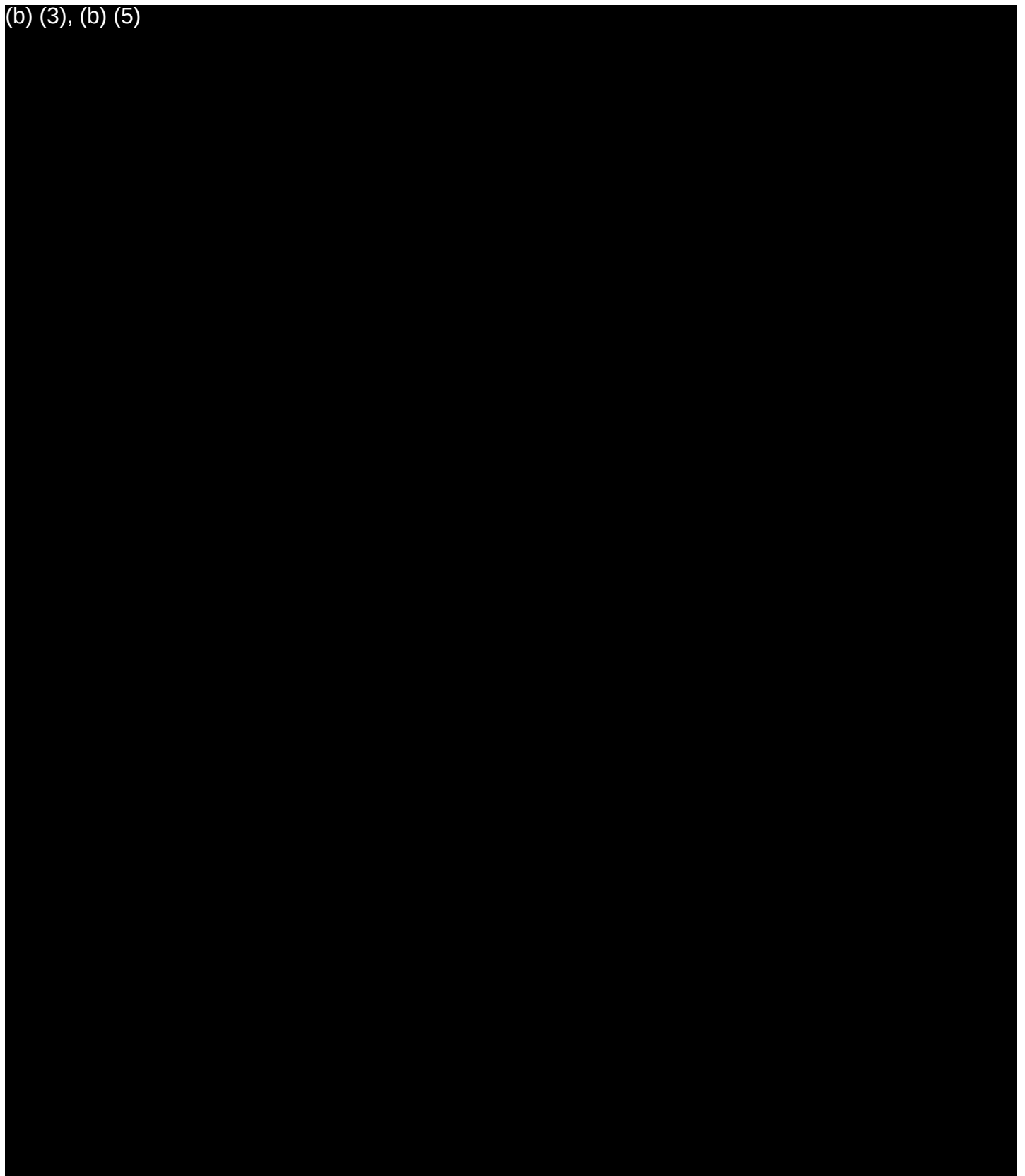
Orion Heat shield IRT Report

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Orion Heat shield IRT Report

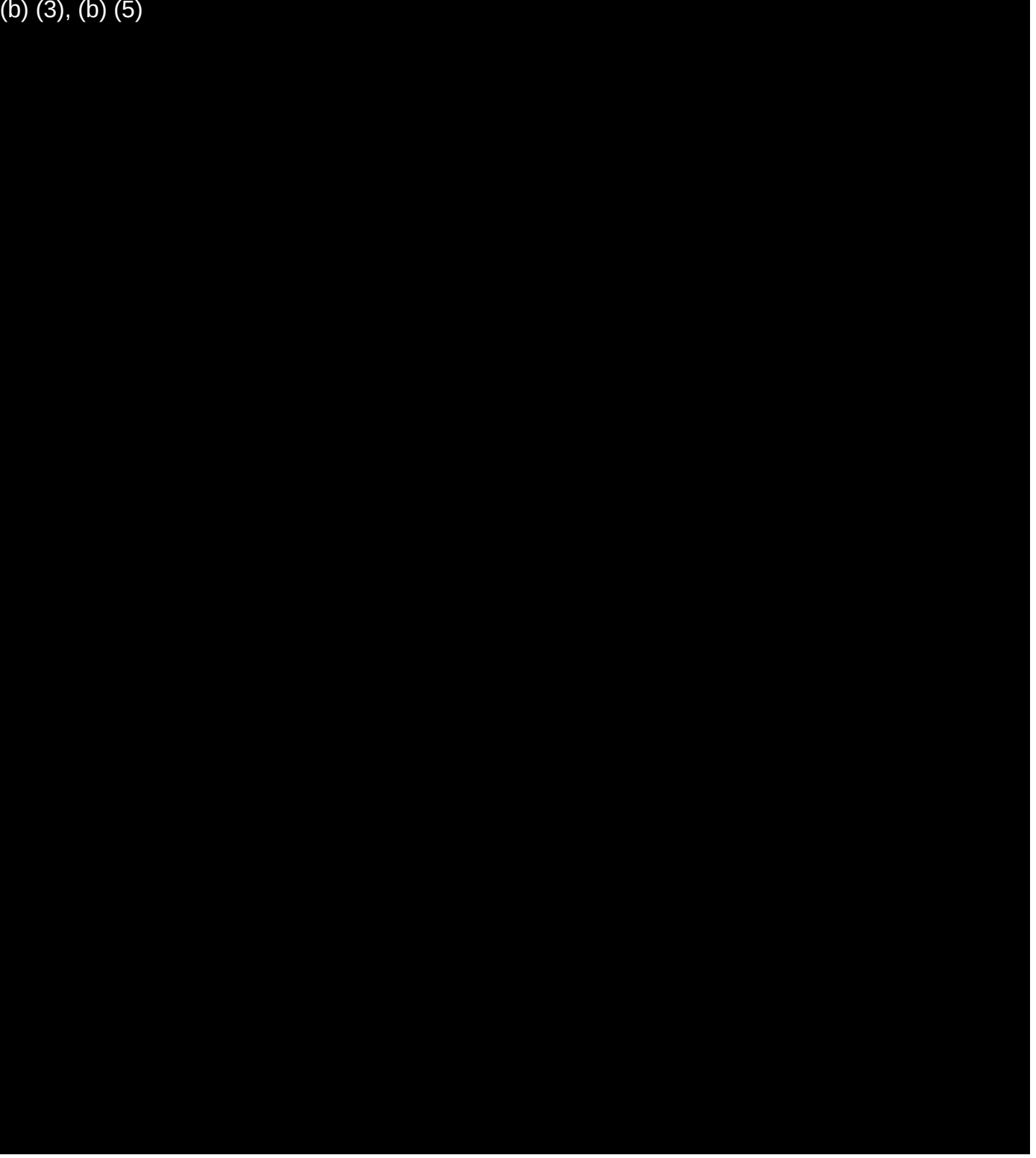
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2.5 Enhancing Engineering Knowledge and Decision-Making

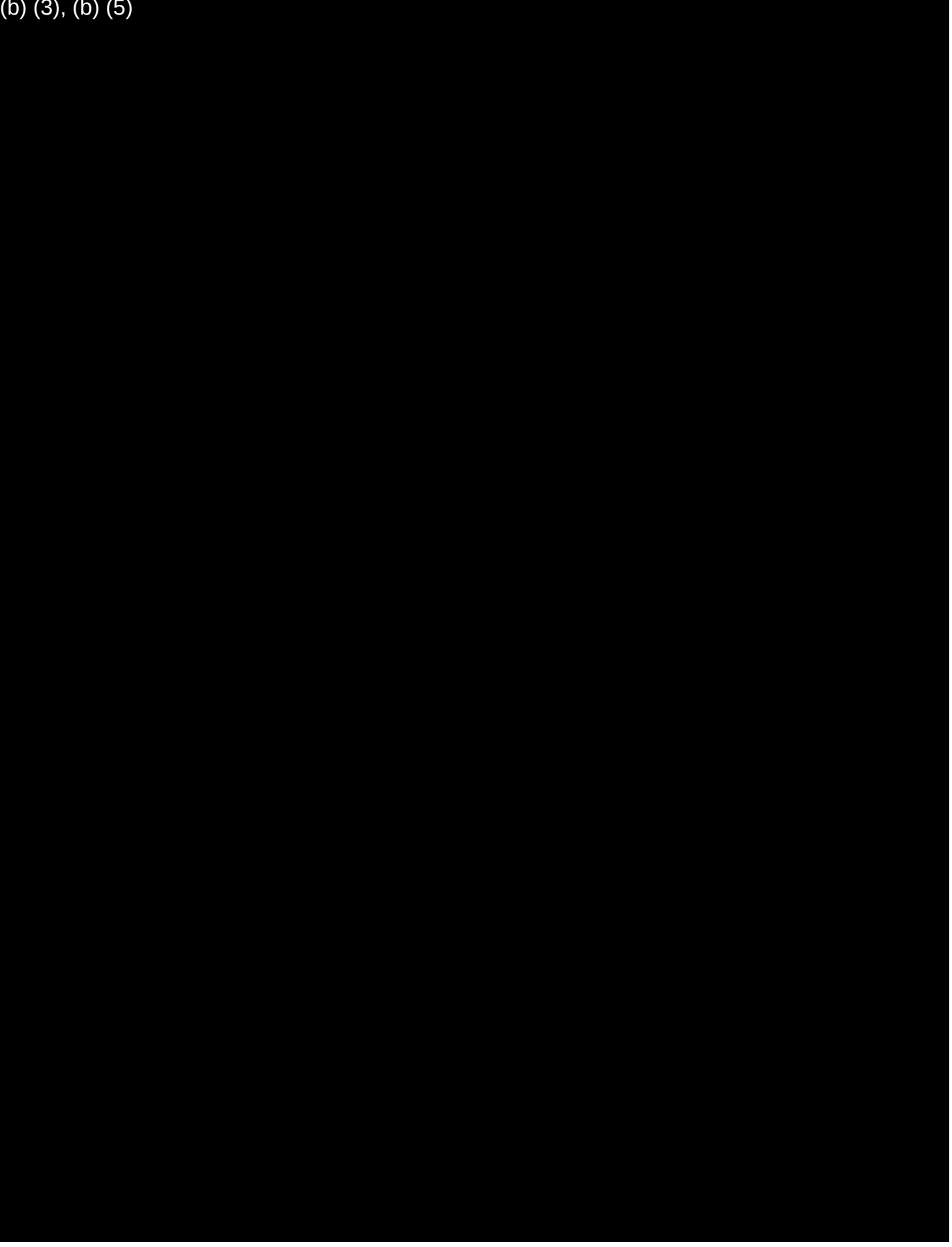
Questions posed by NASA:

(b) (3), (b) (5)



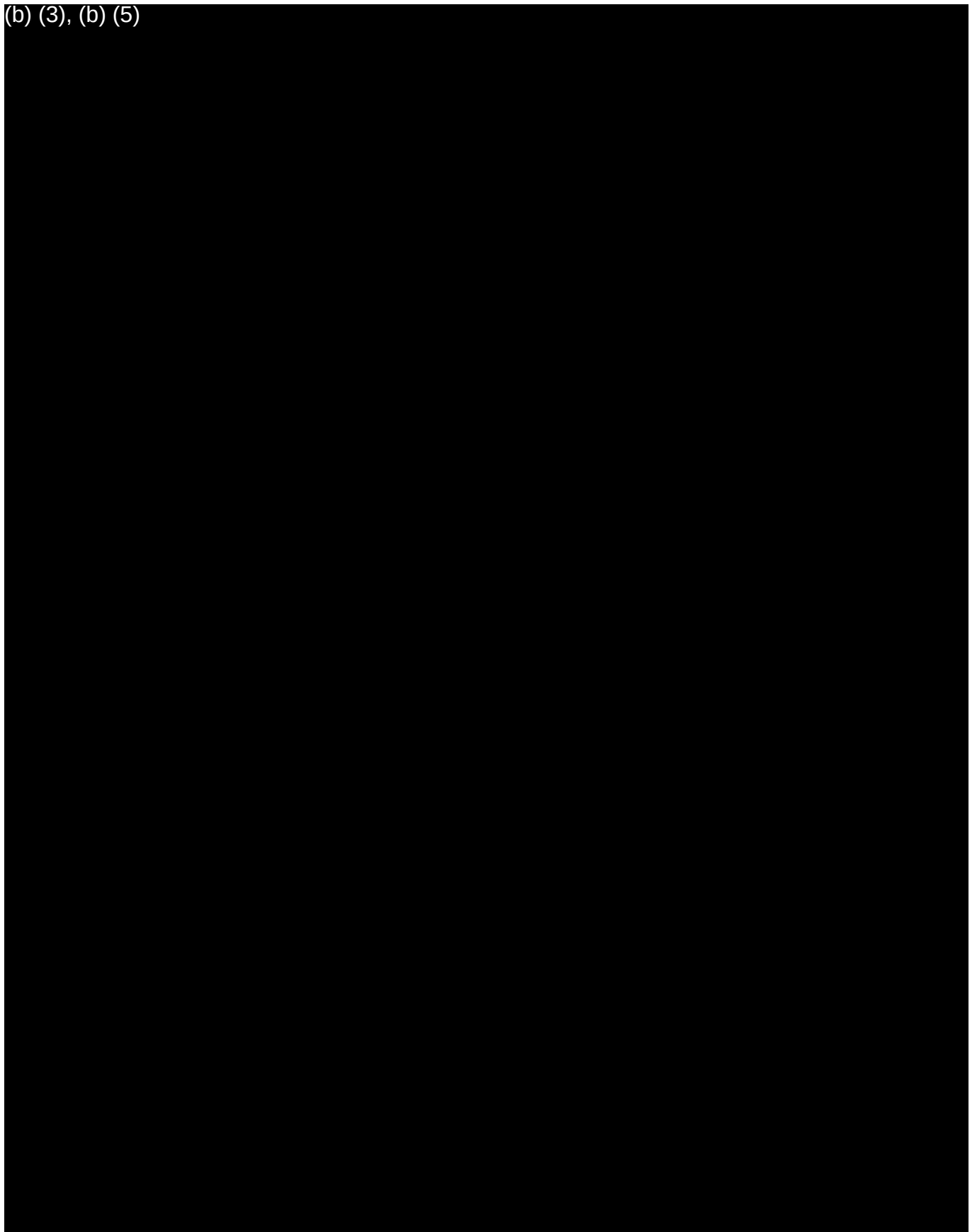
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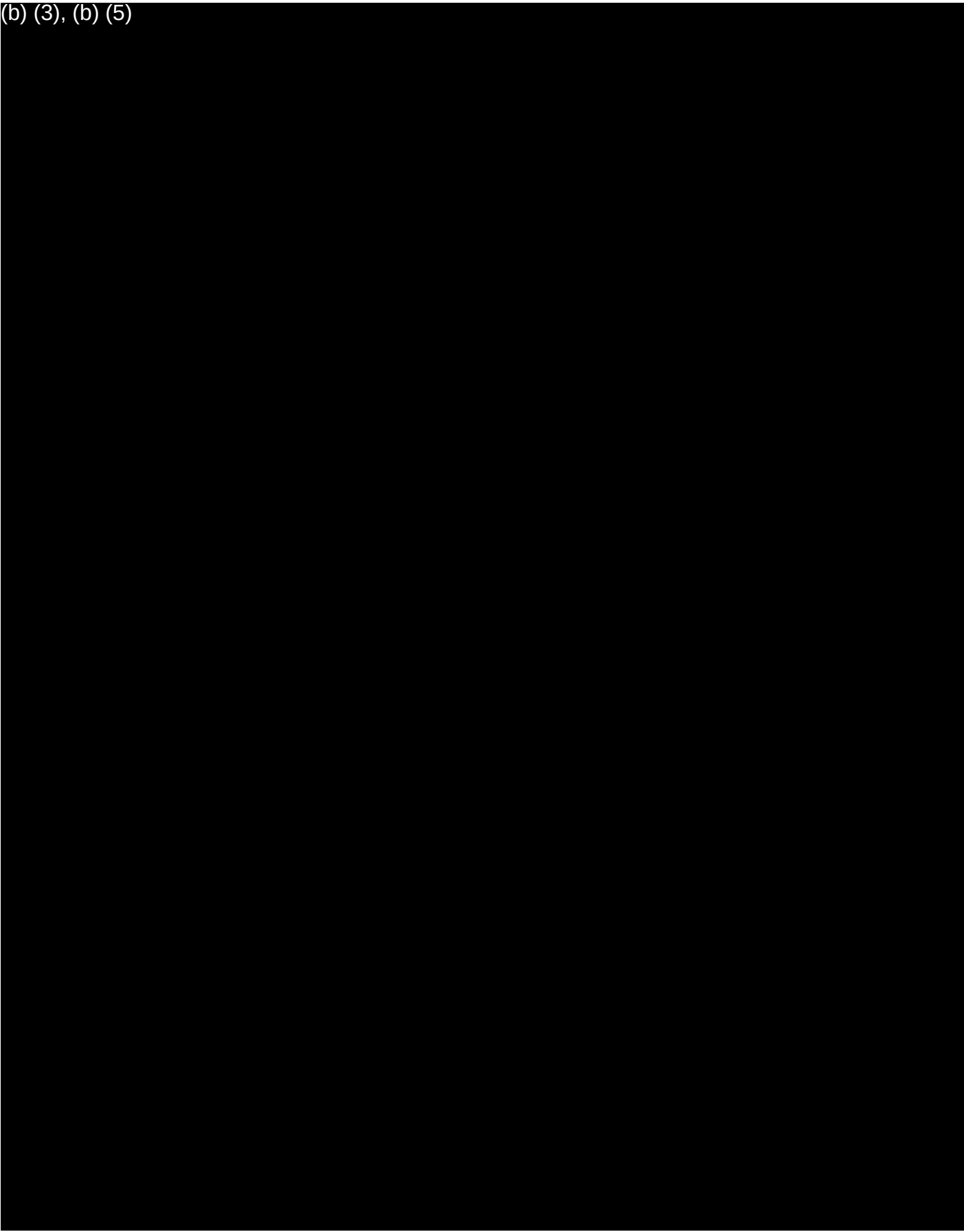
Orion Heat shield IRT Report

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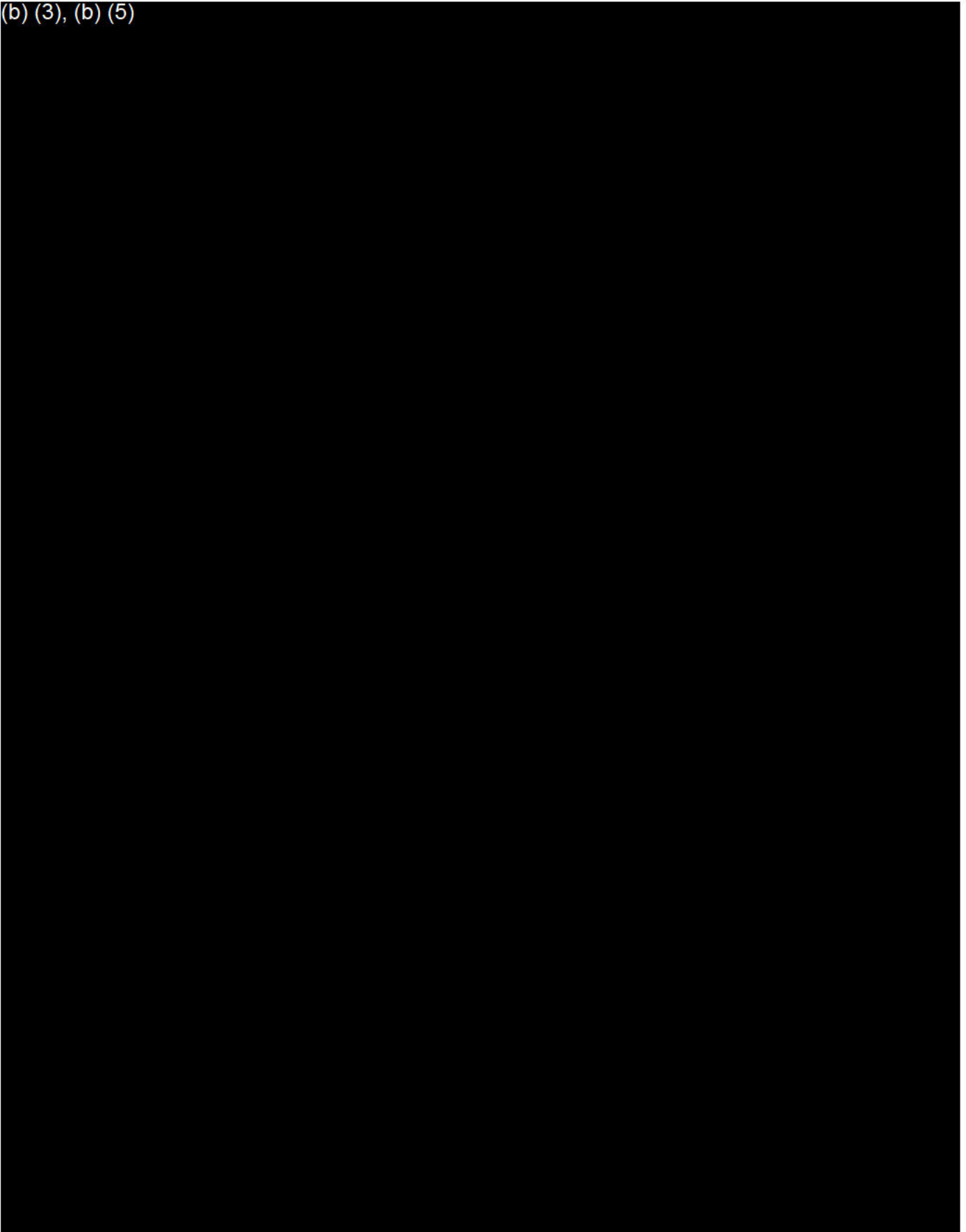
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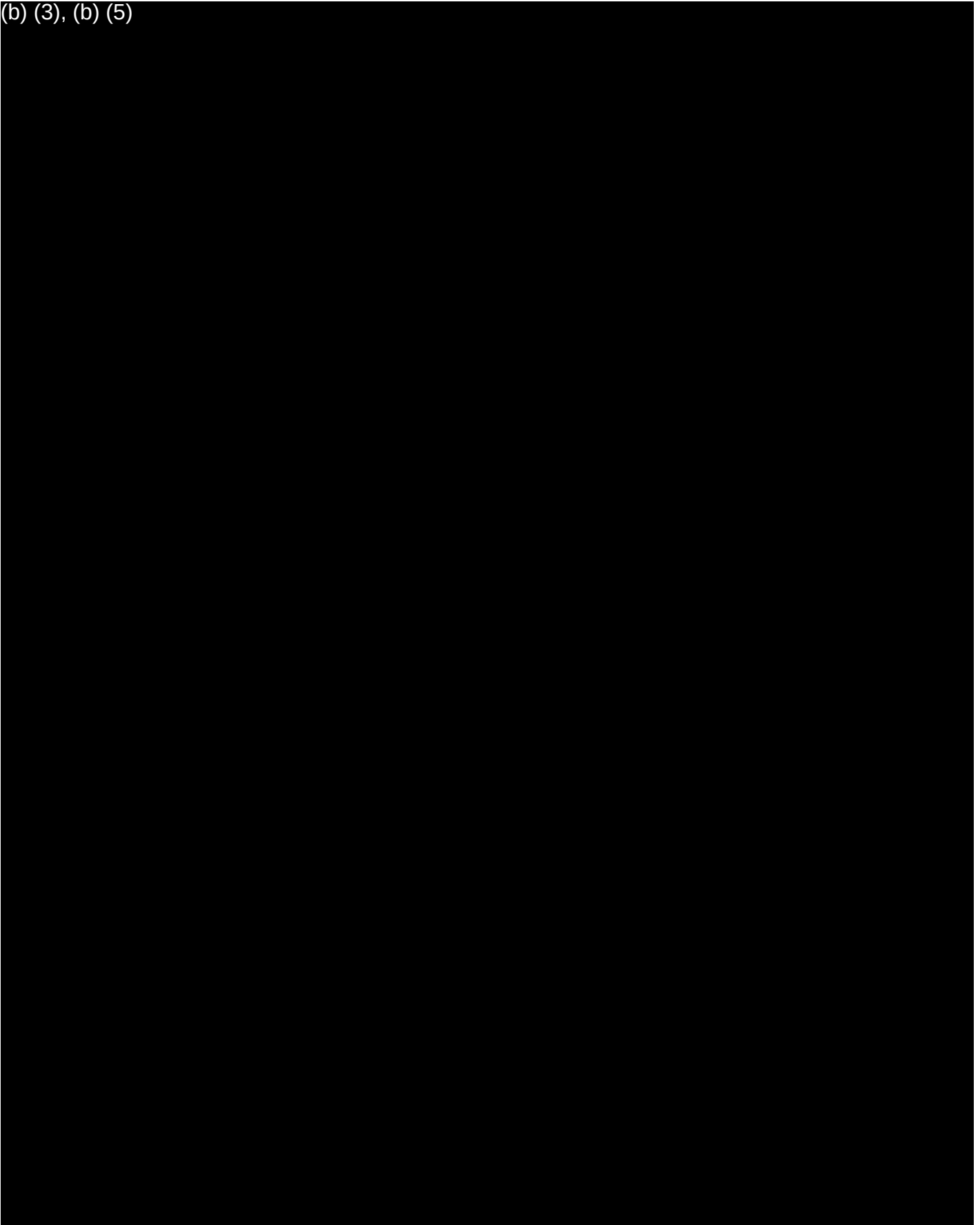
Orion Heat shield IRT Report

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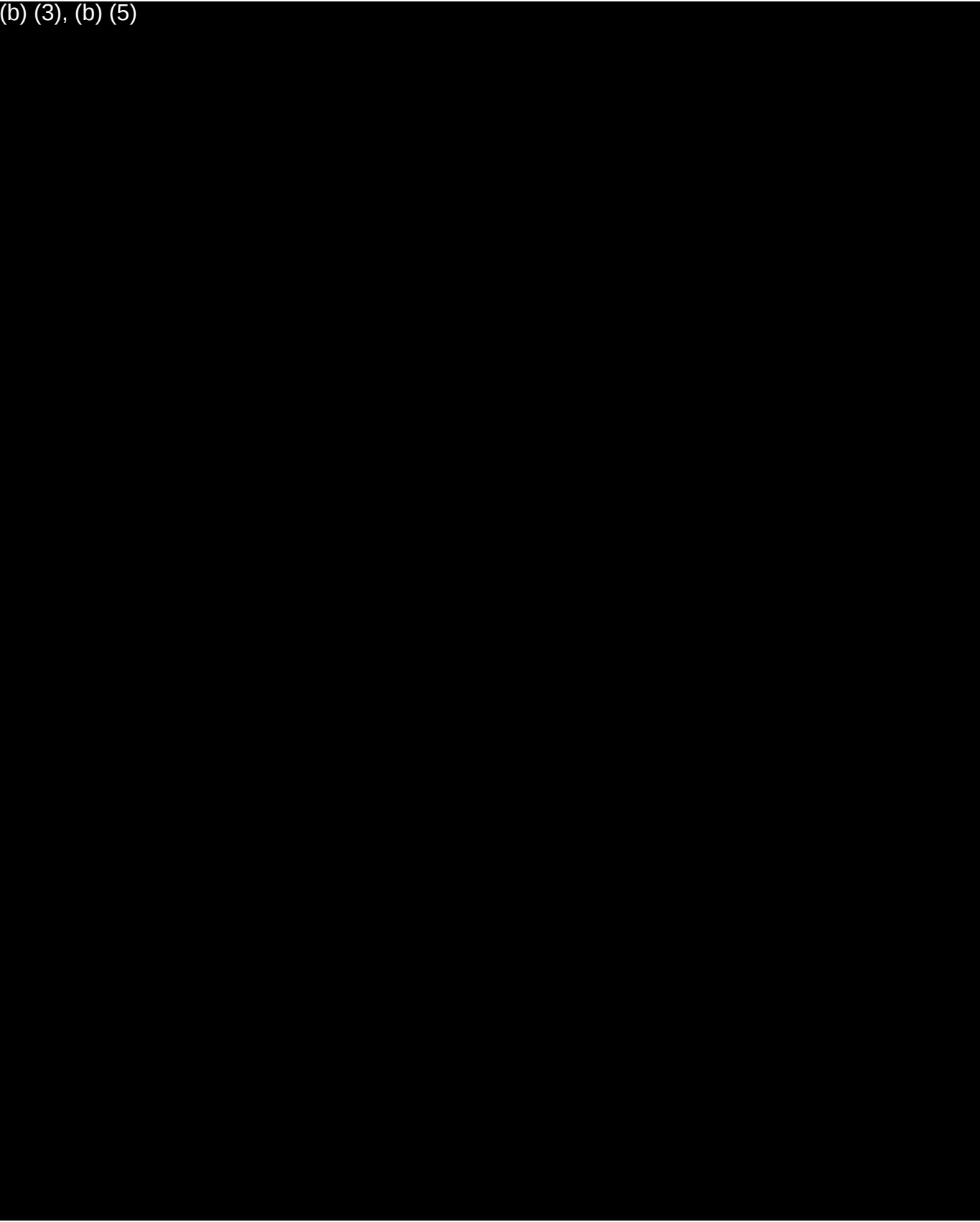


Orion Heat shield IRT Report

(b) (3), (b) (5)



(b) (3), (b) (5)



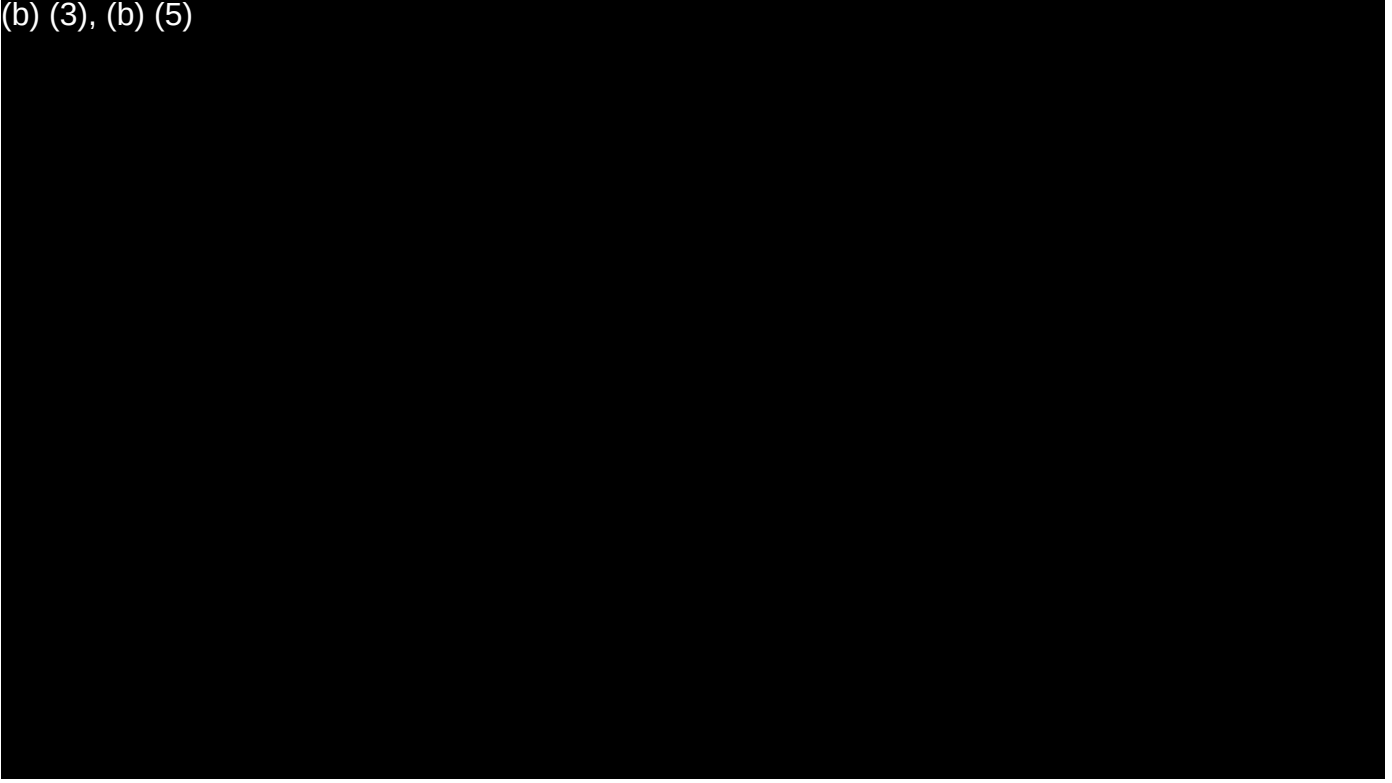
Orion Heat shield IRT Report

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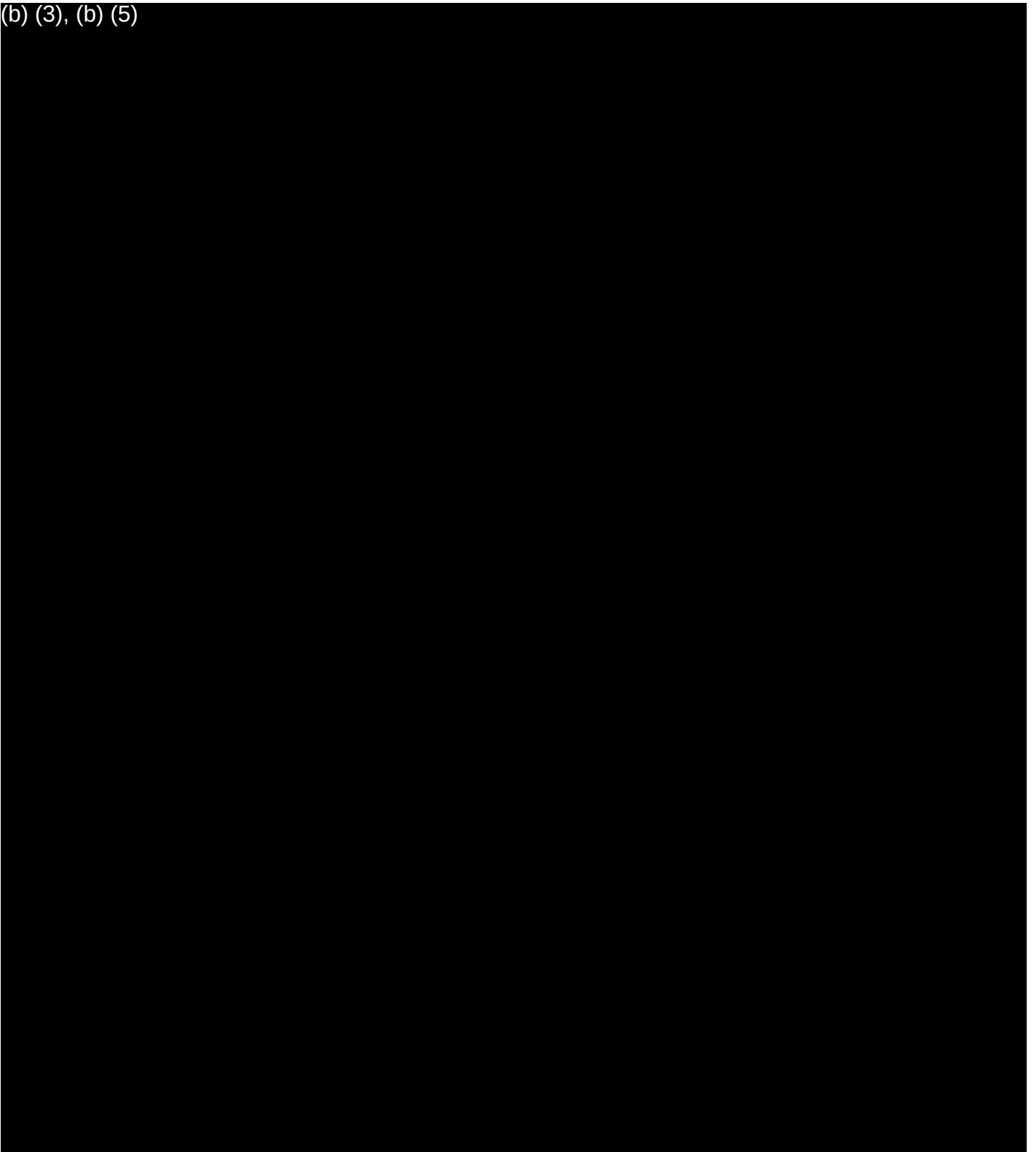
Orion Heat shield IRT Report

(b) (3), (b) (5)



3 Open Work That Could Affect Final Conclusions from this Review

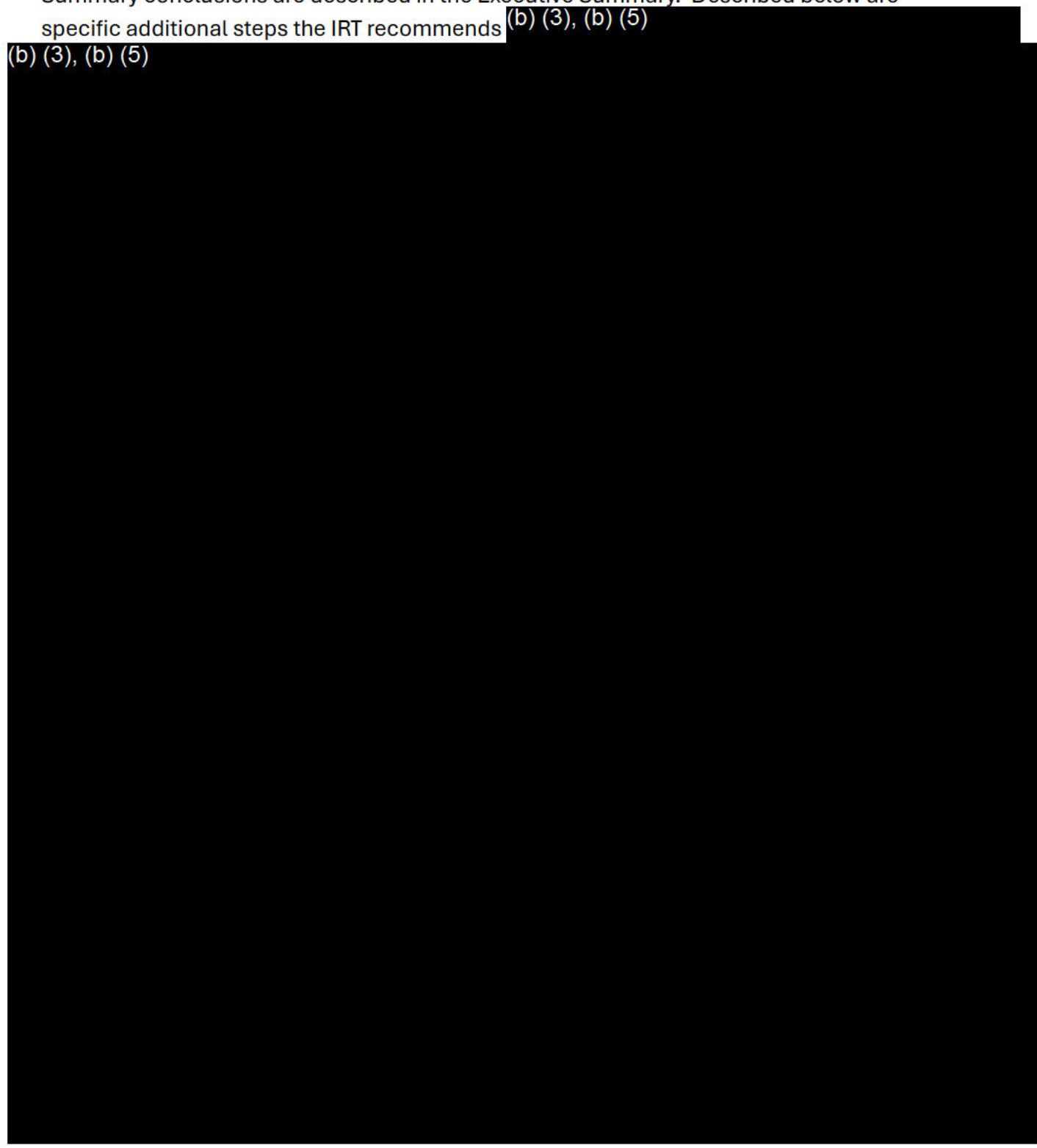
(b) (3), (b) (5)



4 Recommendations

Summary conclusions are described in the Executive Summary. Described below are specific additional steps the IRT recommends (b) (3), (b) (5)

(b) (3), (b) (5)



Orion Heat shield IRT Report

(b) (3), (b) (5)



Appendix A: IRT Charter

Orion Thermal Protection System (Heat shield) Independent Review Team (IRT) Charter March 19, 2024

The Independent Review Team (IRT) is chartered to review and provide assessment of the data that has been generated to date by NASA and its contractors to understand the root cause of the Artemis I Orion heat shield char loss phenomenon and mitigations for future Artemis missions. The review should specifically include (b) (3), (b) (5)

(b) (3), (b) (5)

Purpose

The IRT shall provide an evaluation with comments and recommendations for the following topic area questions:

(b) (3), (b) (5)

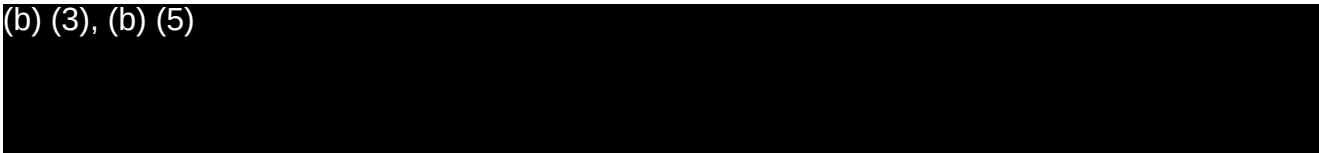
Orion Heat shield IRT Report**IRT Scope**

The IRT will have the ability to:

(b) (3), (b) (5)

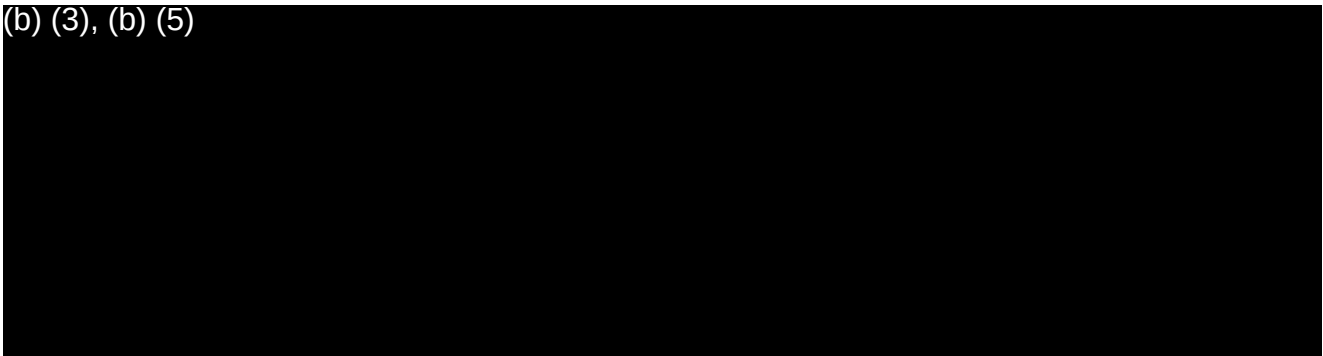


(b) (3), (b) (5)

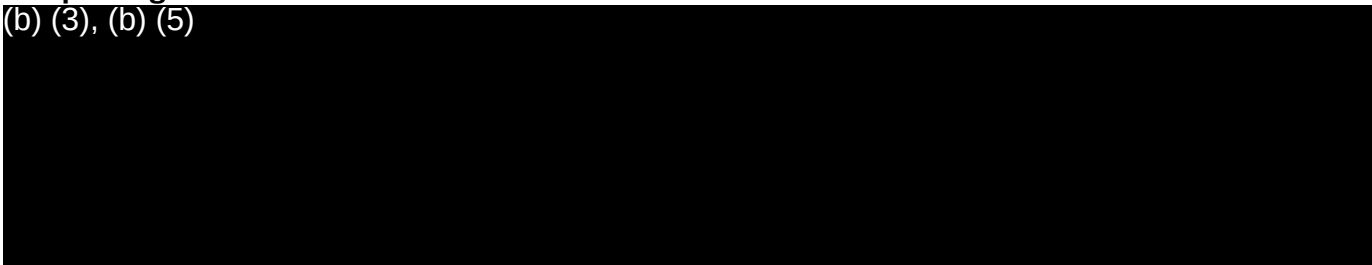
**Review Timeline**

The IRT will commence its review of the available data on April 22, 2024 and have their assessment and recommendations completed by June 7, 2024.

(b) (3), (b) (5)

**Reporting**

(b) (3), (b) (5)



Appendix B: IRT Members

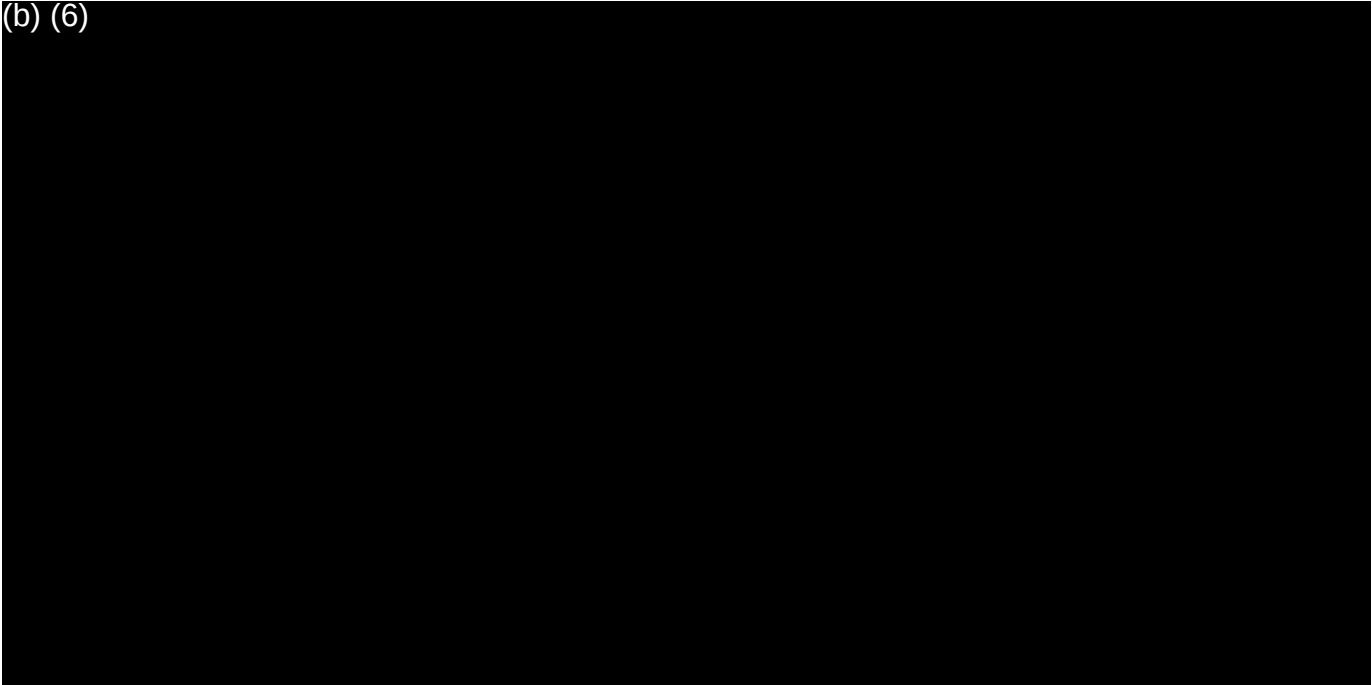
Paul Sean Hill

Author, Speaker, and Principal of Atlas Executive Consultant, LLC, retired Director of Mission Operations, NASA Johnson Space Center, former Shuttle and ISS Flight Director

During his 25 years at NASA, Paul Sean Hill first developed space station construction techniques. He then led flights from Mission Control as a Space Shuttle and International Space Station Flight Director, supporting 24 missions from 1996 through 2005, culminating as the Lead Shuttle Flight Director for the return-to-flight after the Columbia accident. After a series of senior leadership positions, Paul served as the Director of Mission Operations for human spaceflight from 2007 through 2014, responsible for mission planning, flight controller and astronaut training, and flight operations. He currently serves on the NASA Aerospace Safety Advisory Panel and is a Director of the Manned Spaceflight Operations Association.

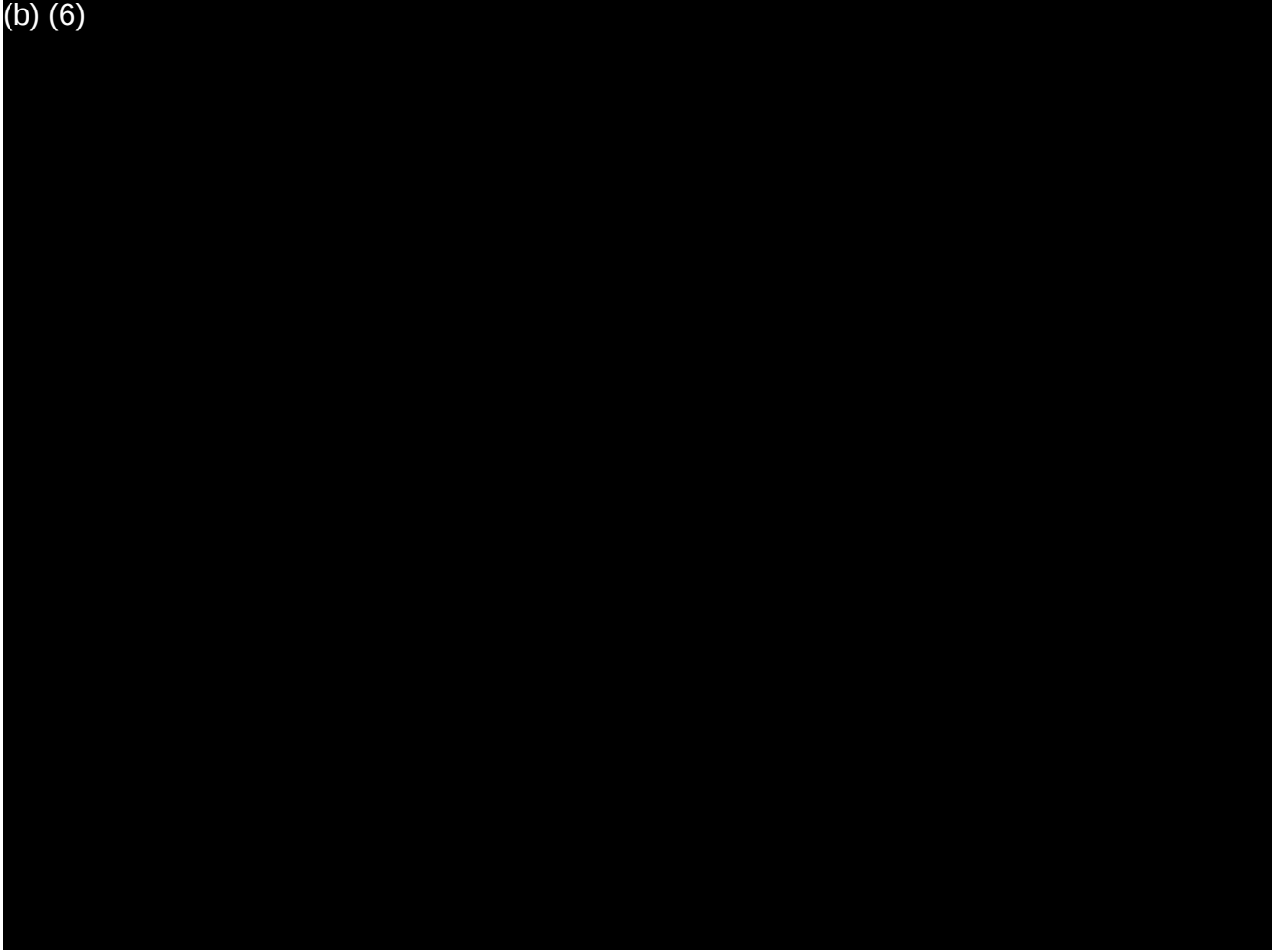
Before his work with NASA, Paul served in the USAF in military satellite operations. He received a BS and MS in Aerospace Engineering from Texas A&M University in 1984 and 1985 and was a member of the Corps of Cadets.

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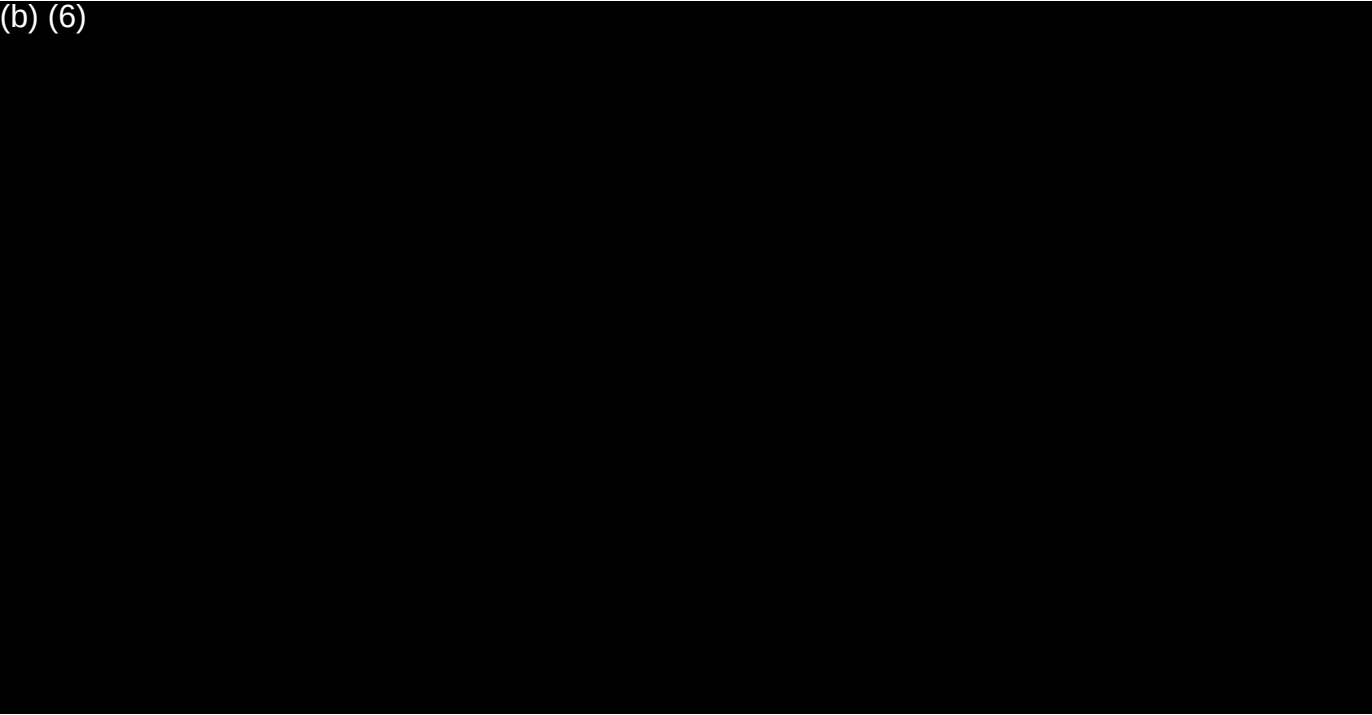


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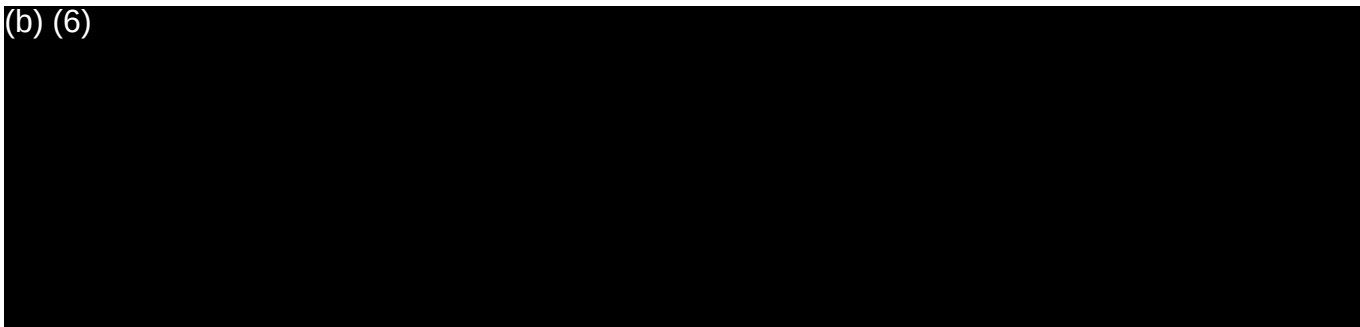
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**Warren “Woody” Hoburg**

NASA Astronaut

Woody Hoburg is a current NASA astronaut. In 2023, he served as Pilot for the SpaceX Crew-6 mission to the International Space Station. During his 186 days in space, he conducted numerous scientific experiments and maintenance activities and conducted two spacewalks to install new ISS Roll-Out Solar Arrays. Prior to NASA, Woody was an Assistant Professor of Aeronautics and Astronautics MIT, where his group developed methods and software to reliably and efficiently design aircraft using convex optimization. His group’s software was used to down select architectures and design a 5-day endurance aircraft for the US Air Force. Prior to MIT, he worked in product development at Boeing Commercial Airplanes.

Woody received a BS in Aerospace Engineering from MIT in (b) (6) and a PhD in Electrical Engineering and Computer Science from UC Berkeley in (b) (6)

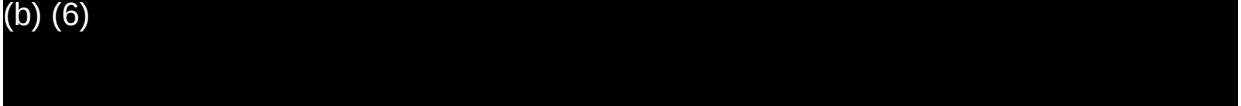
Sarah Howse

Ceramics and Ablatives Team Lead, NASA MSFC Engineering Directorate

Ms. Howse leads a team of multi-discipline engineers and technical specialists in developing, evaluating, selecting, and applying advanced materials technologies for advanced aerospace systems and project proposals. Ms. Howse provides insight, technical advice, and Materials and Processes support to the Space Launch System (SLS) Booster Project Office and the Booster Obsolescence Life Extension (BOLE) Nozzle Subsystem team, specializing in phenolic ablative materials.

Sarah began her career at NASA, Marshall Space Flight Center, in 2001, working as the lead engineer for the Solid Fuel Torch test bed supporting Shuttle/Booster Project through conceptual definition studies and analysis of materials for advanced aerospace systems. Currently, she serves as the Materials and Processing Lead for the Subscale Testing Program at MSFC, supporting the Booster Project Office and commercial partners by providing material development and performance data for solid rocket materials. The Subscale Testing Program includes the thermal performance material screening Plasma Torch Test Bed, the highly adaptable Solid Fuel Torch, the newly developed mid-size Hybrid Rocket Motor, and the large subscale, qualification level Solid Rocket Test Motor.

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**Michael T. Kirsch**

Deputy Director, NASA Engineering & Safety Center

Mike Kirsch currently serves as the Deputy Director of the NASA Engineering and Safety Center (NESC). He previously served as the Manager of the Management and Technical Support Office and as a Principal Engineer in the NESC. While a Principal Engineer, he led a number of NESC Independent Technical Assessments including an alternate design of the Orion Heat Shield Carrier Structure; a study of permeability through carbon graphite composites; a study of the electronic failures within the Toyota Electronic throttle control; design, build, and test of a full-scale composite crew module; and alternate design of the Crew Exploration Vehicle through the Smart Buyer study.

Prior to joining the NESC, he was the Deputy Manager at White Sands Test Facility (WSTF) responsible for planning and directing developmental and operational tests of spacecraft propulsion systems and related subsystems. In preparing for the Deputy Manager position, Mr. Kirsch managed projects and test facilities across WSTF including oxygen hazards analysis and oxygen system and component testing for the International Space Station (ISS), Shuttle Program, and DOD assets. He also served as the Manager of the Hypervelocity Test Facility performing impact testing on a variety of materials for the ISS, SSP, and other spacecraft hardware. Prior to serving as the Deputy Manager, Mr. Kirsch participated in a rotational assignment within the Space Shuttle Program's (SSP) Vehicle Engineering Office at Johnson Space Center where he was the Technical Assistant to the Manager.

He began his career at NASA's White Sands Test Facility (WSTF) in 1989 while completing his degree in Mechanical Engineering from New Mexico State University.

Danny Olivas

Olivas & Associates, Inc., President, former NASA Astronaut

Olivas is presently a consulting expert and member of the NASA Advisory Council. He is a veteran of 2 space shuttle flights and 5 EVAs. With over 35 years in the field of mechanical engineering and materials science, he is also nationally recognized in the area of accident investigations and reconstruction, spanning space and terrestrial environments. During his tenure at NASA he participated in numerous hardware and operational anomaly investigations, including as a team member of the Spacecraft Crew Survivability Investigation following the Columbia Accident in 2003. He additionally was intimately involved in the materials, process, tool, and procedure development for creation of certified on-orbit repair capability of the Reinforced Carbon-Carbon and Thermal Tile TPS

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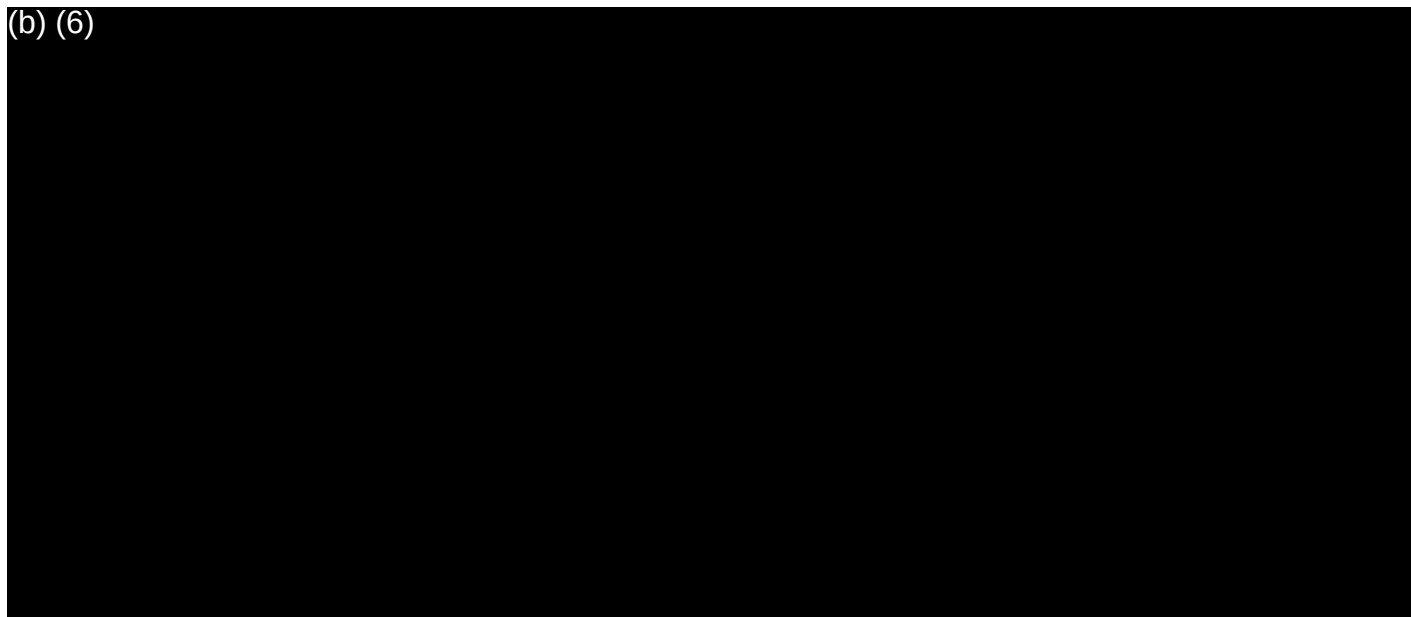
systems prior to NASA return to flight in 2005. In 2007, Olivas performed a TPS repair to the space shuttle Atlantis, following a breach to the system protecting the top side of the port Orbital Maneuvering System engine. During his second EVA on STS-117, he repaired and secured the affected TPS, assuring a successful return through the entry environments and a safe landing at Edwards Air Force Base.

Olivas is recognized by federal and state legal jurisdictions as an expert witness approved to offer testimony in cases involving failure of engineering products and/or operational processes where injury/loss of life or significant property damages has occurred. (b) (6)

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**Dave Schuster**

Adaptive Aerospace Group consultant to the NASA Engineering and Safety Center
Aerosciences Technical Discipline Team, former NASA Technical Fellow for Aerosciences

Dr. Schuster completed a 46-year engineering career in 2023, retiring from the NASA Langley Research Center after 26 years of service. Prior to joining NASA, he held engineering positions at the then Lockheed-Georgia Company as a Scientist in Advanced Flight Sciences where he developed computational aerodynamics tools to evaluate aircraft high lift systems and perform aeroelastic analysis. He was a member of the wing design team for the Advanced Tactical Fighter that eventually became today's F-22 and conducted computational and experimental analyses of numerous aerospace concepts including the National Aerospace Plane. He also helped form the Aerospace Laboratory at the Georgia Tech Research Institute assembling a computational and experimental team to investigate emerging aerospace concepts. He started his NASA tenure as a contractor at NASA Langley Research Center performing aeroelastic simulation and testing for hypersonic and supersonic transports. He joined NASA as a Civil Servant in 1997 where he investigated the Abrupt Wing Stall problem which caused the F-18 E/F wing drop. He also conducted simulations and testing that cleared the Space Shuttle to remove the foam Protuberance Air Loads ramps from the external tank and thus eliminate a substantial foam debris hazard from the vehicle. He served as the Structural and Thermal Systems branch head before joining the NASA Engineering and Safety Center as the NASA Technical Fellow for Aerosciences. With the NESC he led the design effort that defined the launch abort system fairing that is presently on the Orion spacecraft. He served as the aerodynamics lead for the NESC's Max Launch Abort System, and conducted numerous assessments, studies, and tests in cooperation with a broad range of NASA and commercial projects.

Dr. Schuster received his BS in Aerospace Engineering from the University of Cincinnati, and his MS and PhD from the Georgia Institute of Technology.

Orion Heat shield IRT Report**Mairead Stackpoole**

Thermal Protection Materials Branch Chief, NASA Ames Research Center

Mairead Stackpoole is the Branch Chief of the Thermal Protection Materials Branch at NASA Ames Research Center. She has over 20 yrs. experience in TPS development, manufacturing, characterization, and certification. She served as the TPS Manufacturing/Development lead for the Heatshield for Extreme Entry Environments (HEEET) Woven TPS materials development project and is one of the inventors of this TPS concept. She was the technical lead for the PICA sustainability project addressing supply chain issues with the PICA rayon precursor and qualifying sustainable replacements. She served as the Ames OSIRIS REx heatshield POC and managed the Ames OSIRIS REx PICA heat shield related activities. She has supported numerous other TPS-related efforts including serving as the materials lead for the Stardust heatshield post flight analysis project. (b) (6)

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